NASA Technical Paper 1621

Development and Flight Test Results of an Autothrottle Control System at Mach 3 Cruise

Glenn B. Gilyard and John J. Burken

JULY 1980

NASA

NASA Technical Paper 1621

Development and Flight Test Results of an Autothrottle Control System at Mach 3 Cruise

Glenn B. Gilyard and John J. Burken
Dryden Flight Research Center
Edwards, California

NASA
National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1980

DEVELOPMENT AND FLIGHT TEST RESULTS

OF AN AUTOTHROTTLE CONTROL SYSTEM

AT MACH 3 CRUISE

Glenn B. Gilyard and John J. Burken
Dryden Flight Research Center

INTRODUCTION

For aircraft flying at high altitudes and high speeds, accurate control of Mach number is necessary for maximum range performance. In the past, subsonic cruise aircraft have usually controlled Mach number through the pitch axis by elevator commands. However, the high altitudes and high speeds associated with supersonic cruise flight contribute to an unfavorable balance between kinetic and potential energy, and when Mach number is controlled through the elevator large altitude excursions become necessary to correct for small changes in Mach number. The altitude excursions are undesirable from an air traffic control standpoint (current regulations require aircraft to remain within 100 m (300 ft) of a given altitude) and, for commercial air passengers, from a ride qualities standpoint as well.

In response to these problems, a Mach hold system was developed that operates in conjunction with a previously developed altitude hold mode (ref. 1), and the system was flight tested at high speeds and altitudes as part of a research program involving YF-12 series aircraft.

This report presents the flight test results obtained as well as comparisons with the original YF-12 Mach hold system (which used elevator control). Reference 1 describes the first phases of the autopilot improvement program, and reference 2 summarizes the highlights of the altitude hold results and preliminary autothrottle system results.

SYMBOLS AND ABBREVIATIONS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken in Customary Units.

ADC	air data computer
AP	autopilot
a_n	normal acceleration at center of gravity (unless otherwise noted), g
C	conventional Mach hold case
g	acceleration due to gravity, m/sec^2 (ft/sec^2)
h	altitude, m (ft)
K	gain or autothrottle KEAS hold case
K_{θ_h}	altitude gain
$K_{\theta_{KEAS}}$	KEAS gain
K_{θ_M}	Mach gain
KEAS	knots equivalent airspeed
M	Mach number or autothrottle Mach hold case
m	mass, kg (slugs)
PLA	power lever angle, deg
p_s	static pressure, N/m^2 (lb/ft^2)
$p_s(\alpha)$	variation of static pressure with angle of attack
p_{s_1}, p_{s_2}	compensated static pressures (fig. 4), N/m^2 (lb/ft^2)

p_{s_3}	uncompensated static pressure (fig. 4), N/m^2 (lb/ft^2)
p_{t_2}	total pressure, N/m^2 (lb/ft^2)
q_c	impact pressure, $p_{t_2} - p_s$, N/m^2 (lb/ft^2)
R	$= p_{t_2}/p_s$
SAS	stability augmentation system
S	Laplace operator, per sec
T	temperature, °C (°F)
V	velocity, m/sec (ft/sec)
α	angle of attack of wing reference plane, deg
δ_e	elevon deflection, deg
δ_θ	pitch attitude gain (fig. 15(c))
$\delta_{\dot{\theta}}$	pitch rate-to-elevon gain (fig. 15(a))
ζ	damping ratio
θ	pitch attitude, deg
σ	standard deviation
τ_θ	pitch attitude time constant (fig. 15(b))
φ	bank angle, deg

Subscripts:

f	fast
s	slow

A dot over a quantity denotes the time derivative of that quantity.

AIRCRAFT DESCRIPTION

The YF-12C airplane (figs. 1 and 2) is an advanced, twin-engined, delta-winged interceptor designed for long-range cruise at Mach numbers greater than 3.0 and altitudes above 24,400 meters (80,000 feet). Pertinent aircraft physical characteristics are given in reference 3.

Two nacelle-mounted, all-movable vertical tails provide directional stability and control. Each vertical tail is canted inward and pivots on a small stub section attached directly to the top of the nacelle.

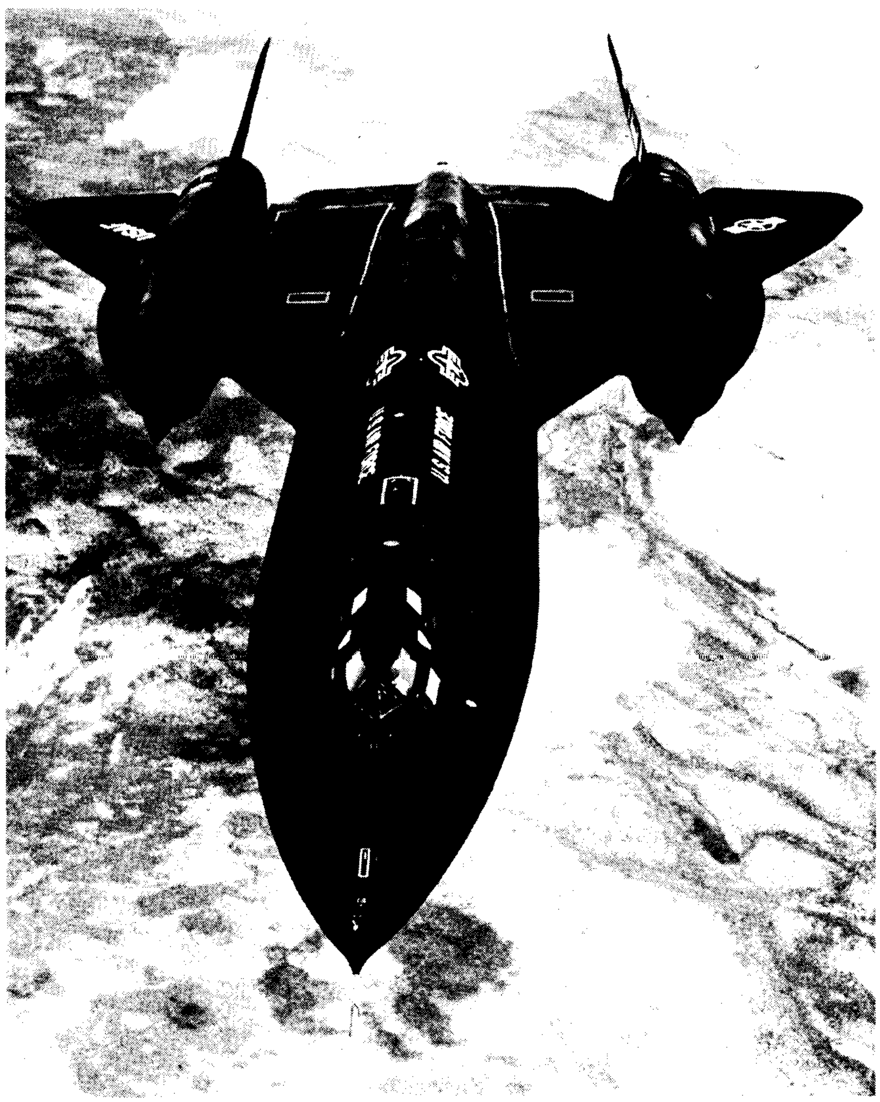


Figure 1. YF-12C airplane.

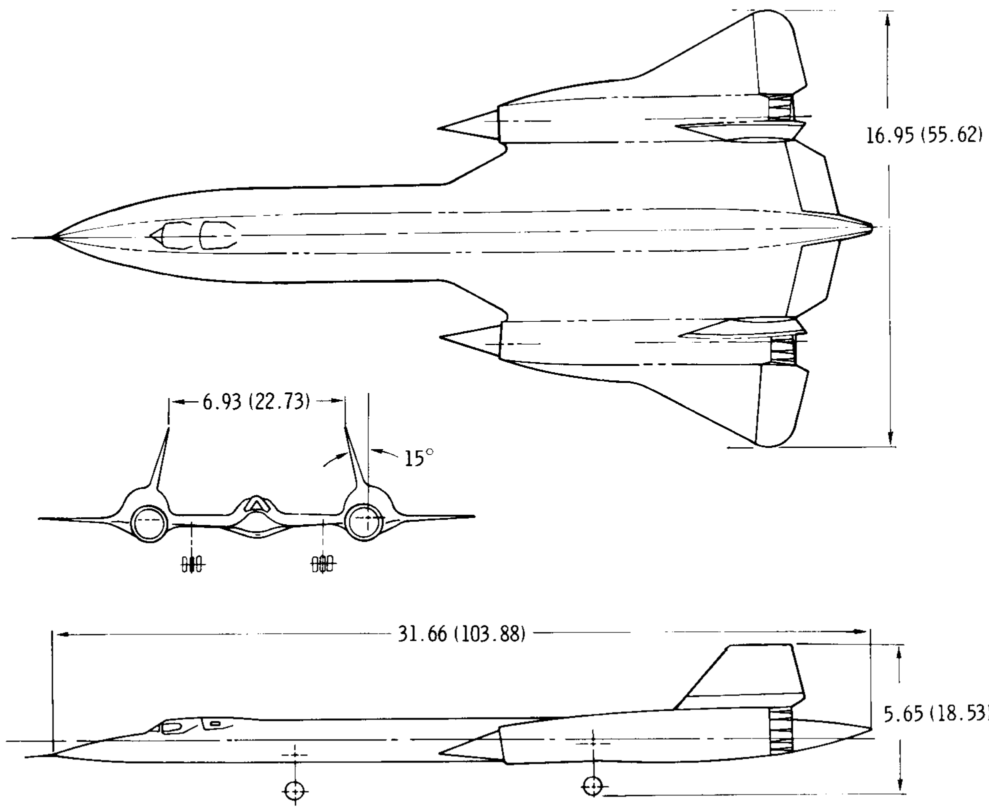


Figure 2. Airplane dimensions (in meters (feet)).

Two elevons on each wing, one inboard and one outboard of each nacelle, perform the combined functions of ailerons and elevators.

The airplane has two axisymmetric, variable-geometry, mixed-compression inlets, which supply air to two J58 engines. Each inlet has a translating spike and forward bypass doors to control the position of the normal shock in the inlet. An automatic inlet control system varies the spike and bypass door positions to keep the normal shock in the optimum position. The pilot can also control the spike and bypass doors manually.

ELEMENTS OF FLIGHT CONTROL SYSTEM

The main elements of the pitch-axis flight control system are the air data sensors, the air data computer, and the autopilot control system. These items are briefly discussed below; a more detailed description of the air data sensors and the air data computer can be found in reference 1.

Air Data Sensors

The air data parameters and static and total pressure are obtained from the compensated nose boom illustrated in figure 3. A more detailed view of the

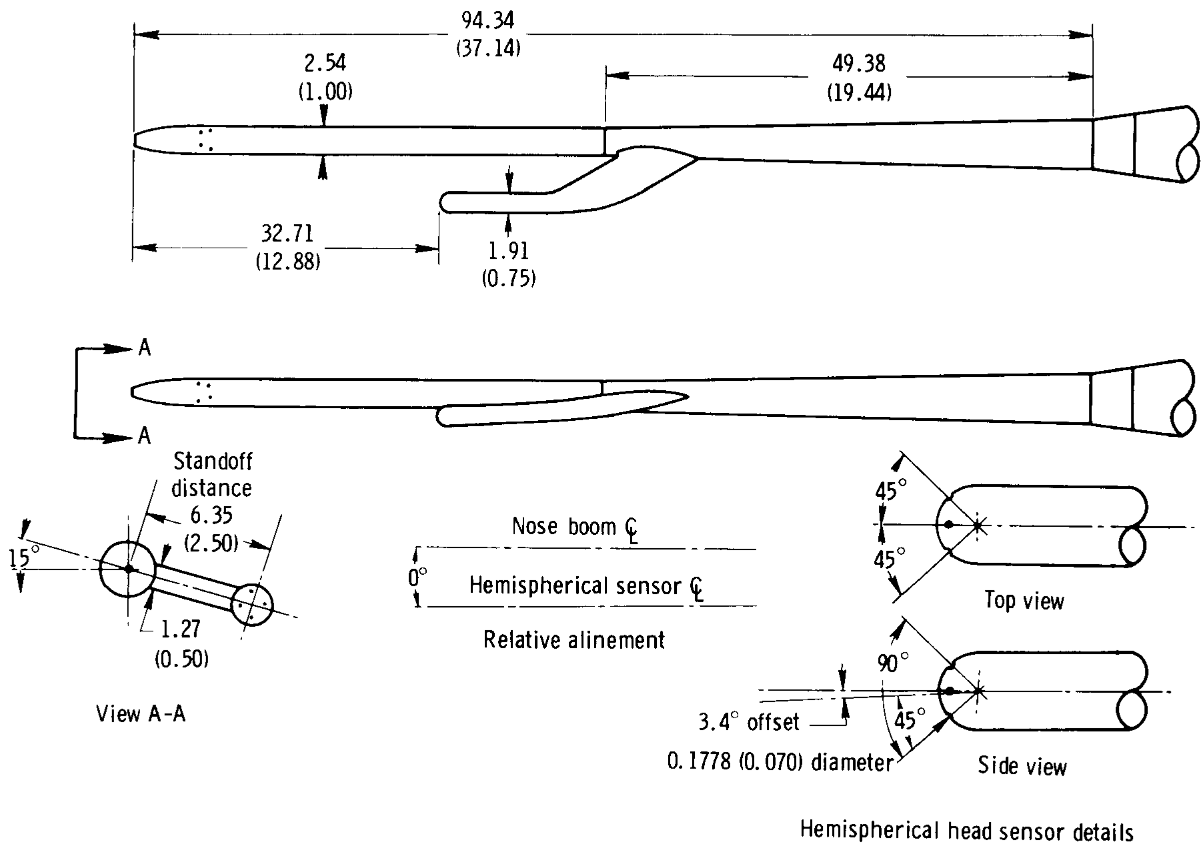


Figure 3. Three-view drawing of nose boom and pitot-static probe showing hemispherical head flow direction sensor. Dimensions in centimeters (inches).

three static pressure sources is presented in figure 4. The air data computer that provides information to the Mach hold and knots equivalent airspeed (KEAS) hold modes of the autopilot is connected to p_{s_2}, which is compensated to minimize position error corrections but, as shown in figure 5, is sensitive to angle of attack.

The variation of static pressure error with angle of attack in figure 5, which is referred to in this report as the nominal $p_s(\alpha)$ variation, was determined from slow pullup-pushover maneuvers 20 to 30 seconds in duration. The nominal $p_s(\alpha)$ variation at Mach 3.0 and 23,600 meters (77,500 feet) at a typical trim angle of attack produces an altitude error of 49 meters (161 feet) per degree of angle of attack, or a Mach number error of 0.011 per degree of angle of attack.

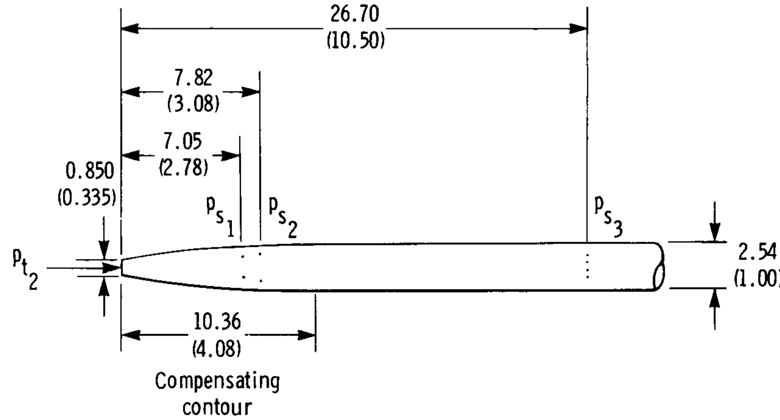


Figure 4. Static pressure source locations on compensated nose boom. Dimensions in centimeters (inches).

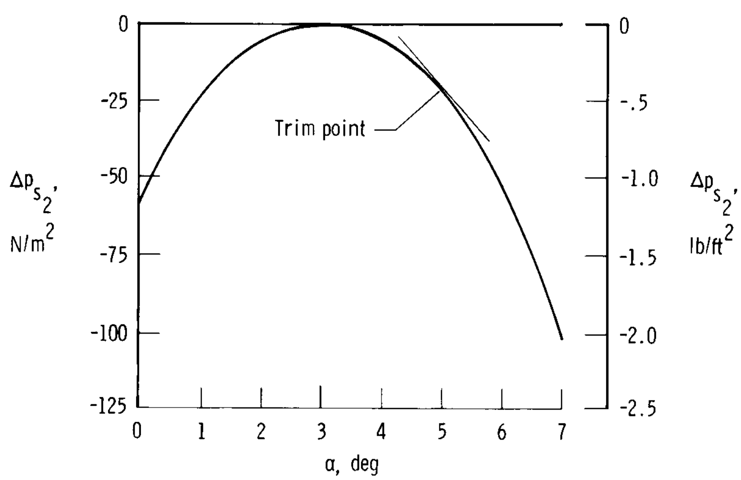


Figure 5. Variation of static pressure error with angle of attack, $p_s(\alpha)$. $M \approx 3.0$; h = 23,600 m (77,500 ft). At the trim point, $\Delta p_{s_2}/\Delta\alpha = -23.9$ N/m^2/deg (-0.50 lb/ft^2/deg), which is equivalent to $\Delta h/\Delta\alpha = 49$ m/deg (161 ft/deg) or $\Delta M/\Delta\alpha = 0.011$/deg.

The air data computer that provides information to the altitude hold mode of the autopilot is connected to p_{s_3}. The p_{s_3} measurements require large position error corrections at transonic speeds but have negligible sensitivity to angle of attack.

Air Data Computer

The air data computer (ADC) is an electromechanical device that receives total and static pressure from the nose boom and computes Mach number and altitude information for the cockpit display and the autopilot. The threshold of the static pressure loop at an altitude of 23,600 meters (77,500 feet) is approximately 3.7 meters (12 feet), and its frequency response is flat to approximately 0.5 radian per second.

Original Autopilot Control System

Figure 6 is a pitch-axis block diagram of the original autopilot control system. The time constant and gains for the autopilot, which were scheduled as a function of flight condition, are given in their entirety in the appendix, but they may be illustrated by the time constant and gains for flight at Mach 3.0 and an altitude of 23,600 meters (77,500 feet), which were as follows:

$\delta_{\dot{\theta}} = 0.46$ deg δ_e/(deg/sec $\dot{\theta}$)

$\tau_\theta = 7.0$ sec

$\delta_\theta = 9.8$ deg δ_e/deg θ

$K_{\theta_{\dot{h}}} = 440$ deg $\theta/\overline{\ln \dot{p}_s}$

$K_{\theta_h} = 90$ deg $\theta/\ln p_s$

$K_{\theta_{\dot{KEAS}}} = 65$ deg $\theta/\overline{\ln \dot{KEAS}}$

$K_{\theta_{KEAS}} = 10$ deg θ/ln KEAS

$K_{\theta_{\dot{M}}} = 30$ deg $\theta/\overline{\ln (\dot{R} - 1)}$

$K_{\theta_M} = 10$ deg $\theta/\ln (R - 1)$

Limiter = 0.106 deg/sec

Mach trim = -10 deg δ_e

The pitch stability augmentation system (SAS) is used full time for normal aircraft operation, and the primary autopilot mode is attitude hold. In addition to the basic attitude hold autopilot, the pilot can select altitude hold, Mach hold, or KEAS hold as an outer loop of attitude hold.

The altitude hold autopilot receives altitude rate and altitude error information from the ADC and commands attitude changes proportional to the altitude rate, altitude error, and integral of altitude error. Similarly, the Mach (or KEAS) hold autopilot receives Mach (KEAS) error information from the ADC and commands attitude changes proportional to the Mach (KEAS) error and the integral of Mach (KEAS) error.

FLIGHT INSTRUMENTATION

A standard set of stability and control parameters was recorded. The angular rate and linear acceleration instrumentation was alined with the body axes. The angle-of-attack indicator was attached as a dogleg on the nose boom, which also contained an airspeed/altitude probe (fig. 3). A fixed four-port pressure-sensing hemispherical head was used to obtain angle-of-attack measurements on the airplane (ref. 4). The lag associated with the hemispherical head was significantly different from that predicted by first-order pneumatic lag theory (ref. 5). The actual angle-of-attack system lag at Mach 3.0 flight conditions was approximately 0.4 second.

In addition, data were recorded at test points within the autopilot control system to analyze system performance and to detect system problems. All the data were recorded on magnetic tape at a minimum of 20 samples per second.

SIMULATION SYSTEM

A digital simulation was implemented to investigate closed-loop aircraft/control system problems. The simulation included aircraft and propulsion dynamics, the control system, and an air data computer model. An integration interval of 20 milliseconds was used for the entire simulation.

The simulation was modeled for flight conditions at Mach 3.0 and an altitude of 23,600 meters (77,500 feet). The simulation was a modification of that described in reference 6 and included the three longitudinal degrees of freedom. Dynamic pressure flexibility corrections were included for pitch control, although no structural modes were simulated. The variation of density with altitude was also included.

High speed inlet operation and the afterburner range of engine operation were represented in sufficient detail to permit the investigation of the aerodynamic and propulsion system interactions. Only normal inlet operation was modeled.

With the exception of the speed stability system, which has no effect at the flight condition of the study, the control system illustrated in figure 6 was implemented. The schedules were programed as functions of static or dynamic pressure, or both. Control system dynamics above 5 hertz were not modeled, since their effect was found to be negligible. A model of the ADC used in the simulation can be found in reference 1.

RESULTS AND DISCUSSION

Conventional Mach Hold Performance

The original Mach hold mode of the YF-12C autopilot was conventional in that Mach number deviations were compensated for by elevator commands that caused changes in altitude. For low speed aircraft, this control scheme works well, since speed can be changed by relatively small changes in altitude. However, as cruise speed increases, the altitude changes required to effect a given change in speed increases.

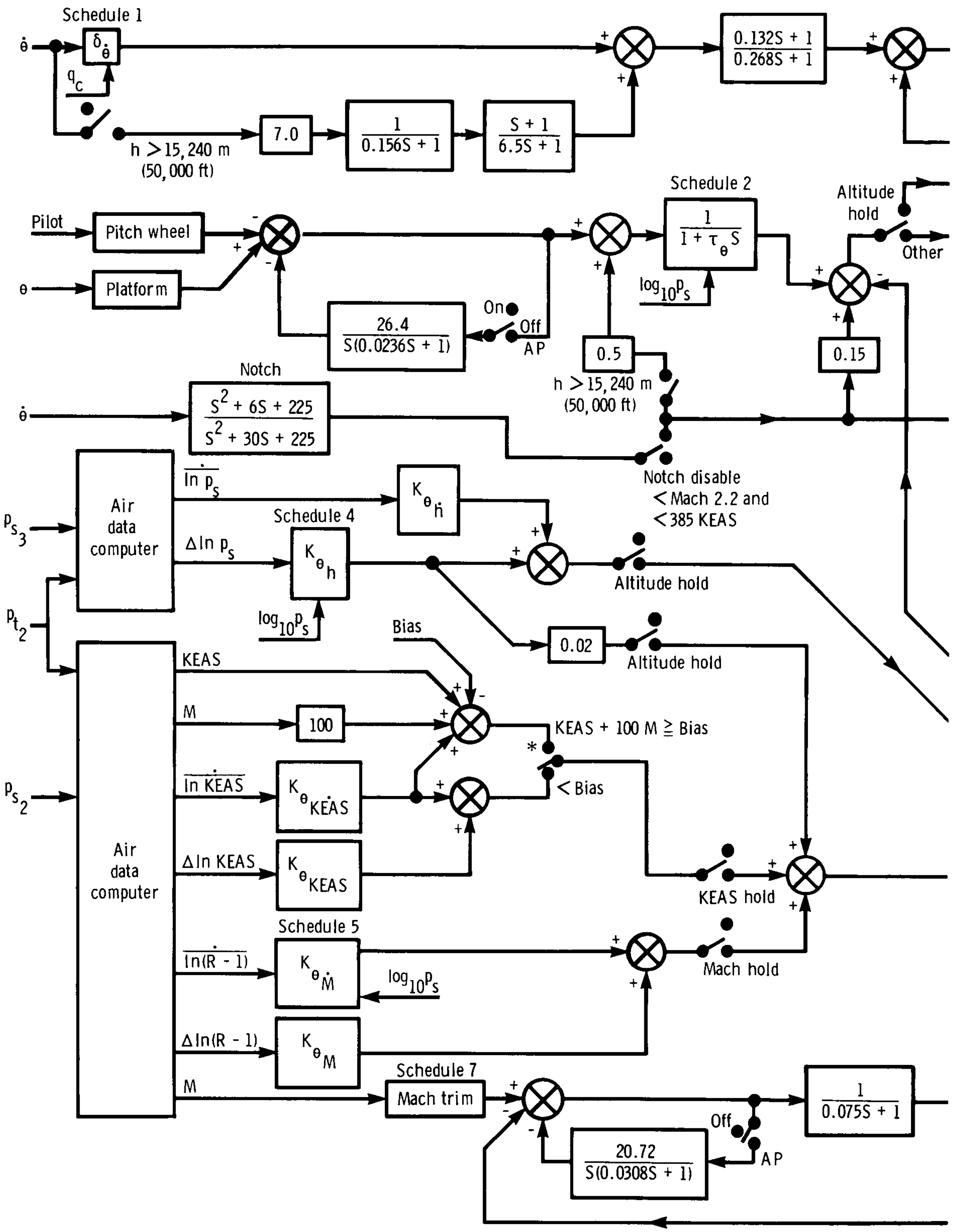
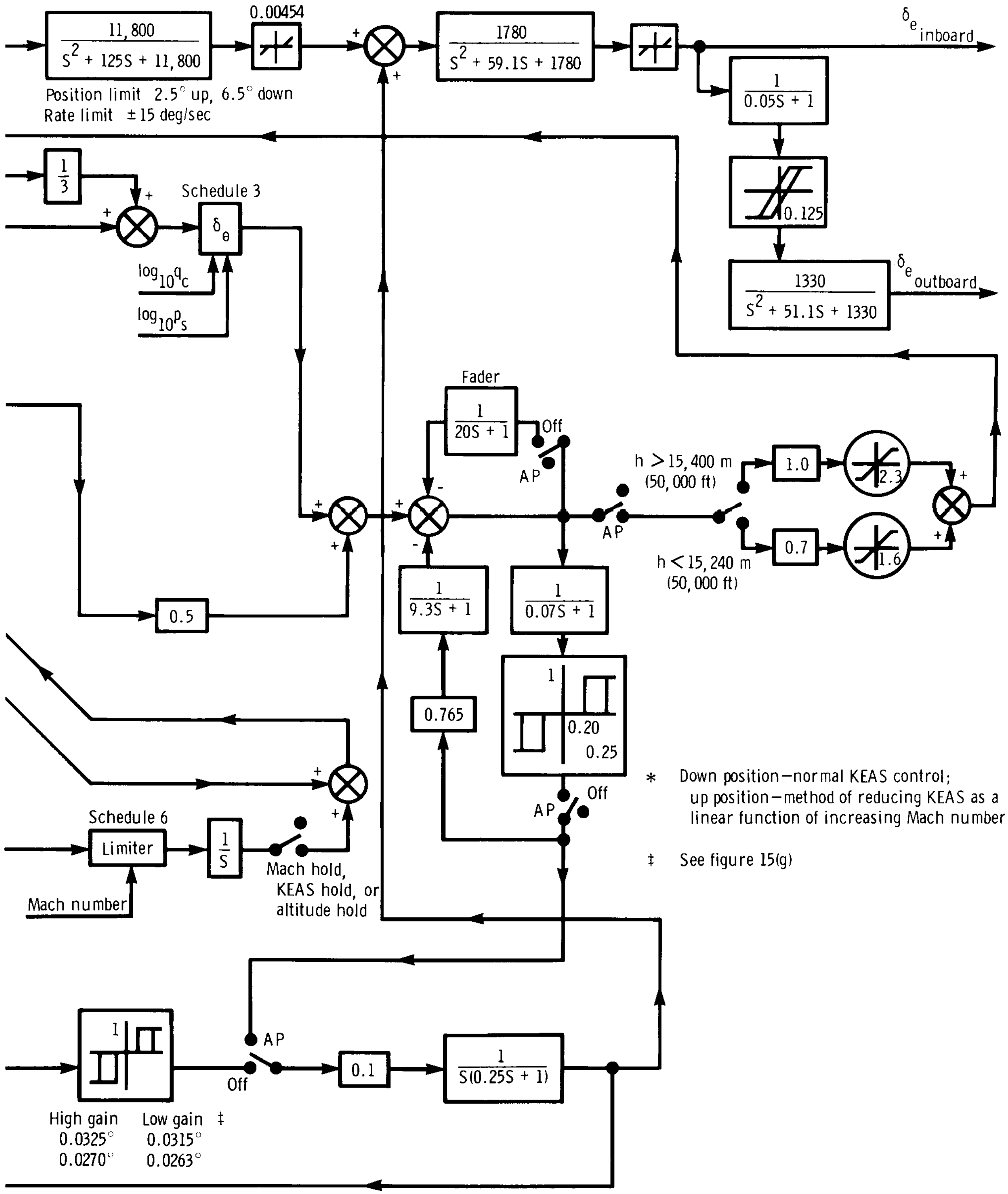


Figure 6. Pitch-axis block diagram for the original YF-12C



autopilot control system. Schedules are given in the appendix.

The theoretical basis for this type of control is that an aircraft tends to fly at constant total energy (if the throttles are kept fixed) for small variations in velocity and altitude. If total energy is expressed as the sum of kinetic plus potential energy,

$$\text{Total energy} = \text{Kinetic energy} + \text{Potential energy}$$

and is constant. In other words, $\frac{1}{2} mV^2 + mgh$ is constant. Thus, if an aircraft is at a constant total energy condition, a variation in velocity is accompanied by a compensating change in altitude, and vice versa.

The velocity (kinetic energy) versus altitude (potential energy) relation is illustrated in figure 7 for a subsonic jet, the Concorde, and the YF-12C aircraft at

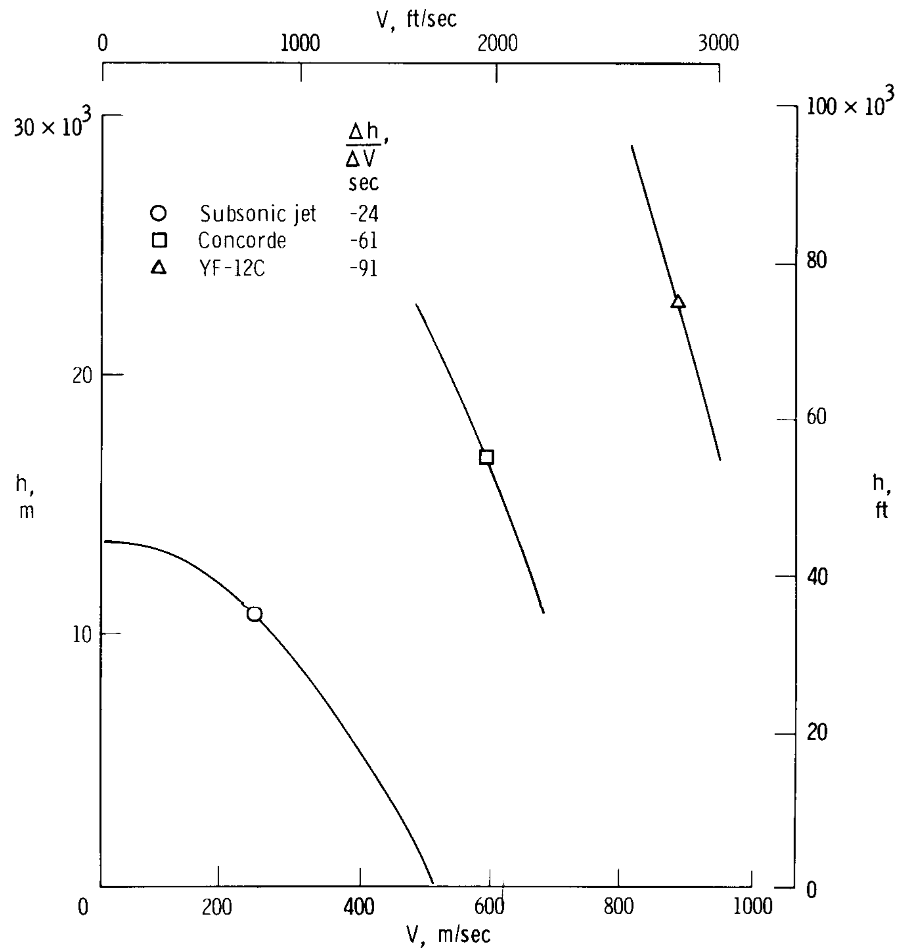


Figure 7. Variation of altitude with velocity for different levels of constant energy.

typical cruise conditions. The altitude change required to compensate for a given speed change is 2.5 times as great at the Concorde flight conditions as at the subsonic jet flight conditions and 3.8 times as great for the YF-12C flight conditions as for the subsonic jet flight conditions.

The conventional Mach hold mode of the YF-12C autopilot (fig. 6) was designed to operate over the entire Mach number range of the aircraft. At speeds greater than Mach 2.0, the desired Mach number could be held quite accurately (±0.02 of a given Mach number) for wings-level conditions. In turns, however, both control over Mach number and ride qualities deteriorated, particularly at the higher Mach numbers. Although the difficulty of controlling Mach number in a turn did not receive much attention, the problem seems to be related to the automatic navigation mode of the autopilot, which commands bank angle and causes increasingly strong coupling with the longitudinal axis with increasing bank angle. An example of the performance of the conventional Mach hold mode at Mach 2.85 is presented in figure 8. The first

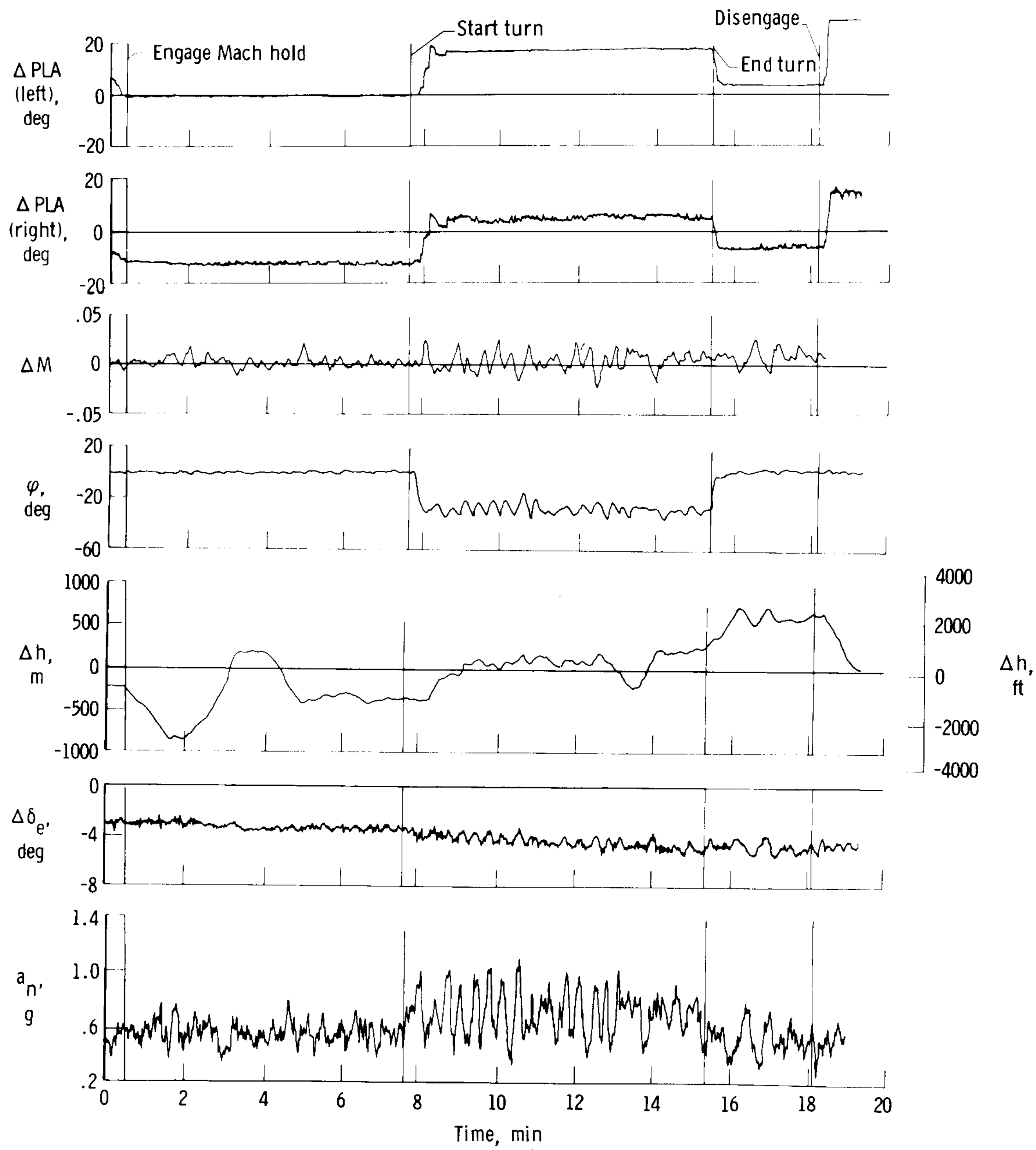


Figure 8. Conventional Mach hold for the YF-12C airplane. Mach 2.85.

7.5 minutes of the time history show wings-level flight, and Mach number deviates only ±0.02. It should be noted that the ride was rough, as evidenced by the ±0.2 g normal acceleration levels, and a peak-to-peak altitude change of 1066 meters (3500 feet) occurred. Seven and a half minutes of data were obtained in turning flight with a bank angle of approximately 35°. In the turn, the quality of Mach hold was slightly degraded ($\Delta M \approx \pm 0.025$), as were ride qualities (±0.35 g normal acceleration). A peak-to-peak altitude change of 610 meters (2000 feet) was encountered during the turn.

It was obvious from this and other maneuvers (ref. 1) that although the conventional Mach hold mode controlled Mach number fairly accurately, the associated ride qualities in terms of normal acceleration would be unacceptable to commercial passengers.

Autothrottle Definition

The previous section illustrates the need for a different Mach control scheme and the desirability of simultaneous altitude control. The system that was developed uses an autothrottle to control speed (Mach number or KEAS) and an altitude hold mode that works through the elevator. A detailed description of the development of the altitude hold mode, which had to be capable of control at altitudes above 21,300 meters (70,000 feet), can be found in reference 1.

The final autothrottle configuration (fig. 9) was designed to control either Mach number or KEAS. The Mach error (or KEAS error) signal is the same as that

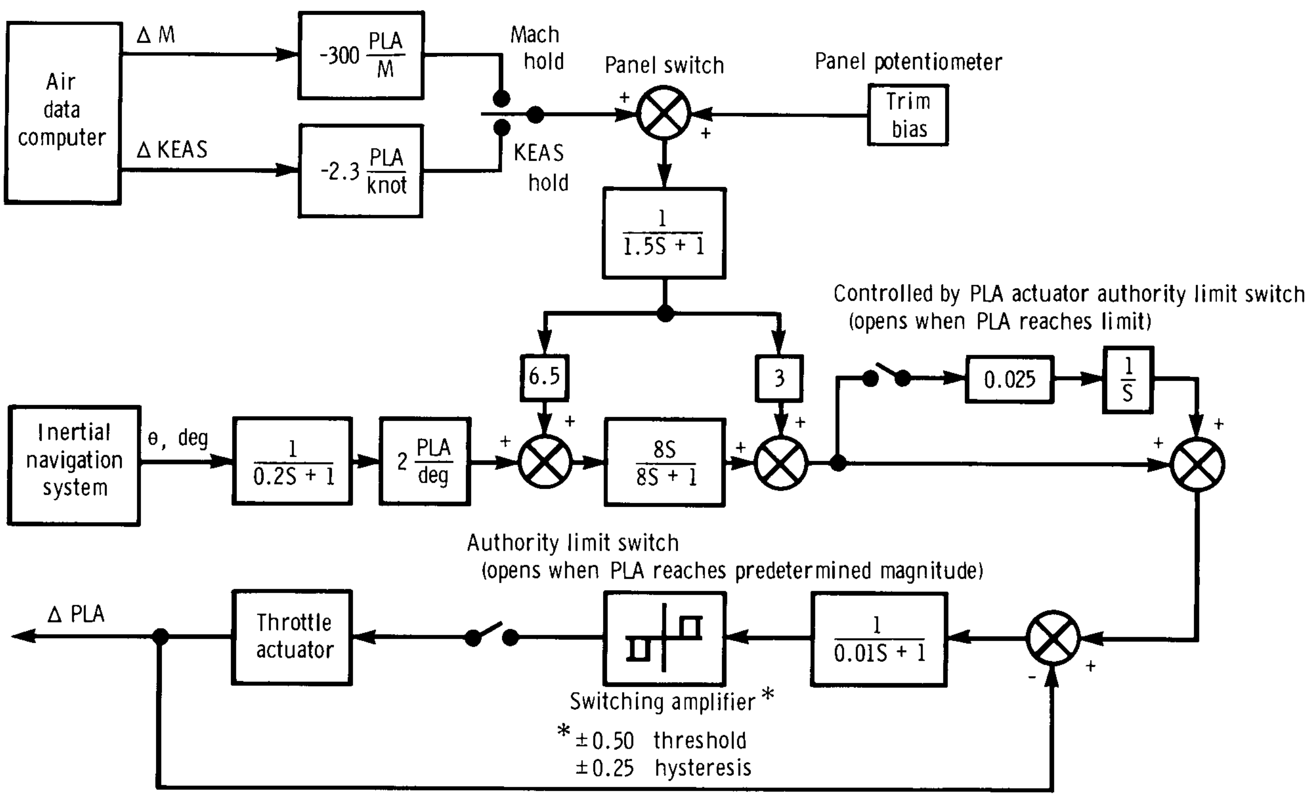


Figure 9. Autothrottle control system.

provided to the basic autopilot. The error signal is passed through a noise filter and split in two; one path is proportional and the other is high passed to provide some lead. The sum of these two signals is then operated on to provide a proportional plus integral signal, which is used as the actuator command. Pitch angle was also sent to the high pass filter to provide lead to compensate for significant attitude changes; however, since in flight the autothrottle was used with the altitude hold mode engaged, attitude variations were negligible. The integrator is disabled when the throttle lever actuator reaches the limit of its authority. If this disabling did not occur whenever the actuator was at its limit, the throttle command would become excessive and would result in low frequency limit cycles.

The actuator control loop consists of the high frequency noise filter output, which feeds a relay with threshold and hysteresis, which in turn commands a constant rate electric actuator. The displacement signal is fed back to provide an error signal. Flight tests were conducted with both fast and slow throttle actuators, which yielded rates of 5.77° of power lever angle (PLA) per second and 0.98° of PLA per second, respectively. As implemented on the aircraft, autothrottle authority was limited to ±15° of power lever angle. In addition, operation was restricted to the afterburner range of the engine, preventing cycling from affecting engine life.

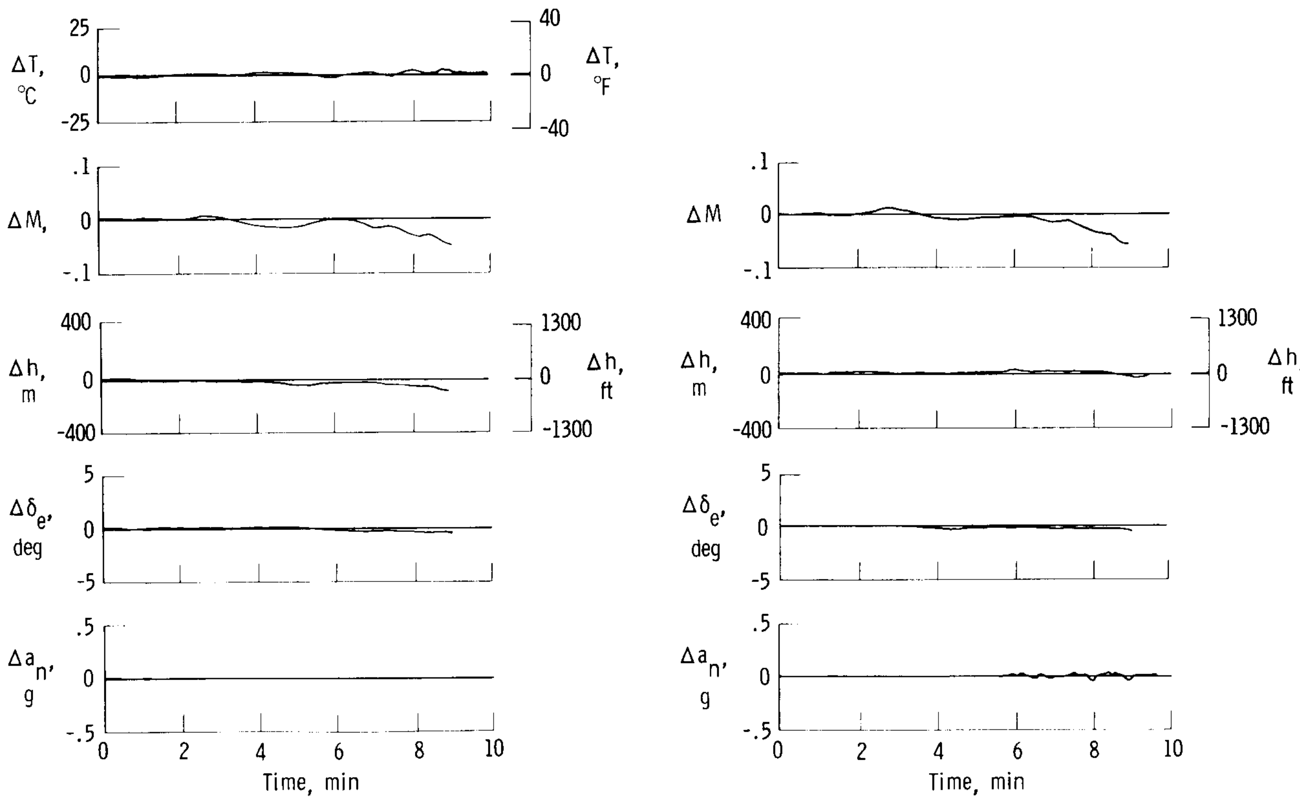
Simulation Studies

Speed control at high altitudes and high speeds is greatly affected by ambient temperature stability (or lack of it), since Mach number changes occur in proportion to ambient temperature changes. To determine the effect of temperature variation on aircraft dynamics using various control schemes, flight test simulations were run using two temperature profiles. One is a 9-minute temperature variation of 2.4° C (4.3° F) peak to peak, referred to hereafter as a nominal variation. The other is a 2-minute temperature variation of 11° C (20° F) peak to peak, a temperature variation that was actually encountered during an XB-70 flight (ref. 7). This variation is referred to hereafter as extreme. The aircraft control schemes investigated are: attitude hold; altitude hold; conventional Mach hold; and autothrottle Mach hold combined with altitude hold.

Simulations of the aircraft's response to the nominal and extreme temperature variations are presented in figures 10 and 11, respectively. The simulated condition is Mach 3.0 and an altitude of 22,100 meters (72,500 feet).

The response of attitude hold to the nominal and extreme temperature variations is shown in figures 10(a) and 11(a), respectively. In both cases, attitude was essentially constant ($\Delta\theta = \pm 0.03°$ for the nominal case and $\pm 0.07°$ for the extreme case), but altitude drifted off and Mach number was uncontrolled. The ride is smooth for the nominal case and acceptable ($\Delta a_n = 0.05\ g$ peak to peak) in the extreme case.

The altitude hold simulation runs are presented in figures 10(b) and 11(b). Altitude is held accurately (15 m (50 ft) peak to peak) and ride is good for the nominal case. In the extreme case, altitude is still held well (±18 m (±50 ft)), but

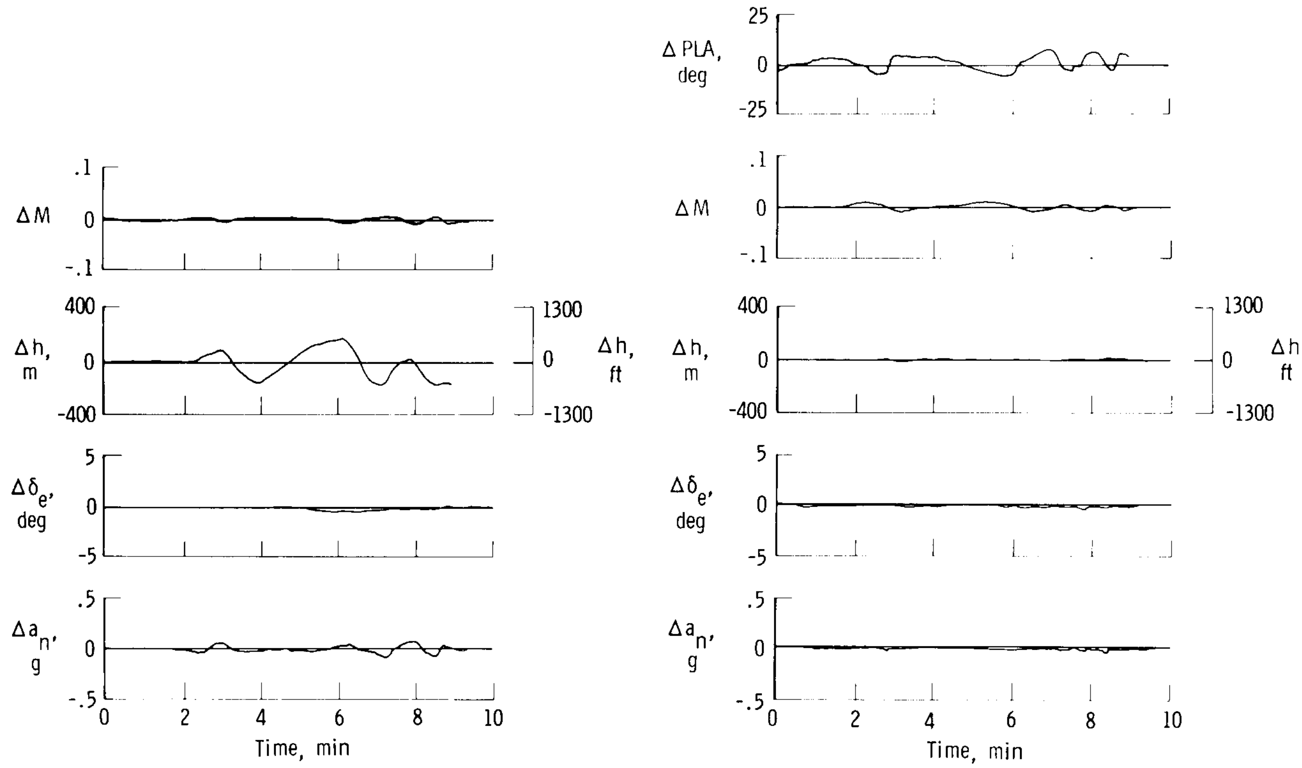


(a) Attitude hold. *(b) Altitude hold.*

Figure 10. Simulated aircraft response to nominal temperature variations with different types of control.

the ride is poor ($\Delta a_n = 0.12$ g peak to peak). In both cases, Mach number drifts off, as with attitude hold.

Conventional Mach hold simulation runs are presented in figures 10(c) and 11(c). In the nominal case, Mach number is held reasonably accurately (±0.01), although control of the high frequency variations is slight. The associated altitude variation is large (336 m (1200 ft) peak to peak). The resulting variations in normal acceleration are 0.12 g peak to peak, and although this level is probably not disturbing in terms of ride qualities, it is significant in view of the mildness of the temperature variation.



(c) Mach hold.

(d) Autothrottle Mach hold and altitude hold.

Figure 10. Concluded.

In the extreme case, Mach number is essentially uncontrolled, the peak-to-peak altitude variation is 518 meters (1700 feet), and ride is clearly unacceptable (Δa_n = 0.40 g peak to peak).

Simulations of autothrottle Mach hold combined with altitude hold are presented in figures 10(d) and 11(d) for the nominal and extreme cases, respectively. In the nominal case, Mach number is held well, although not noticeably better than with conventional Mach hold. However, as compared with the Mach hold system, altitude is controlled accurately, and ride qualities improve.

In the extreme case (fig. 11(d)), Mach number cannot be controlled because of limited excess thrust; however, overall aircraft response is significantly better than with conventional Mach hold.

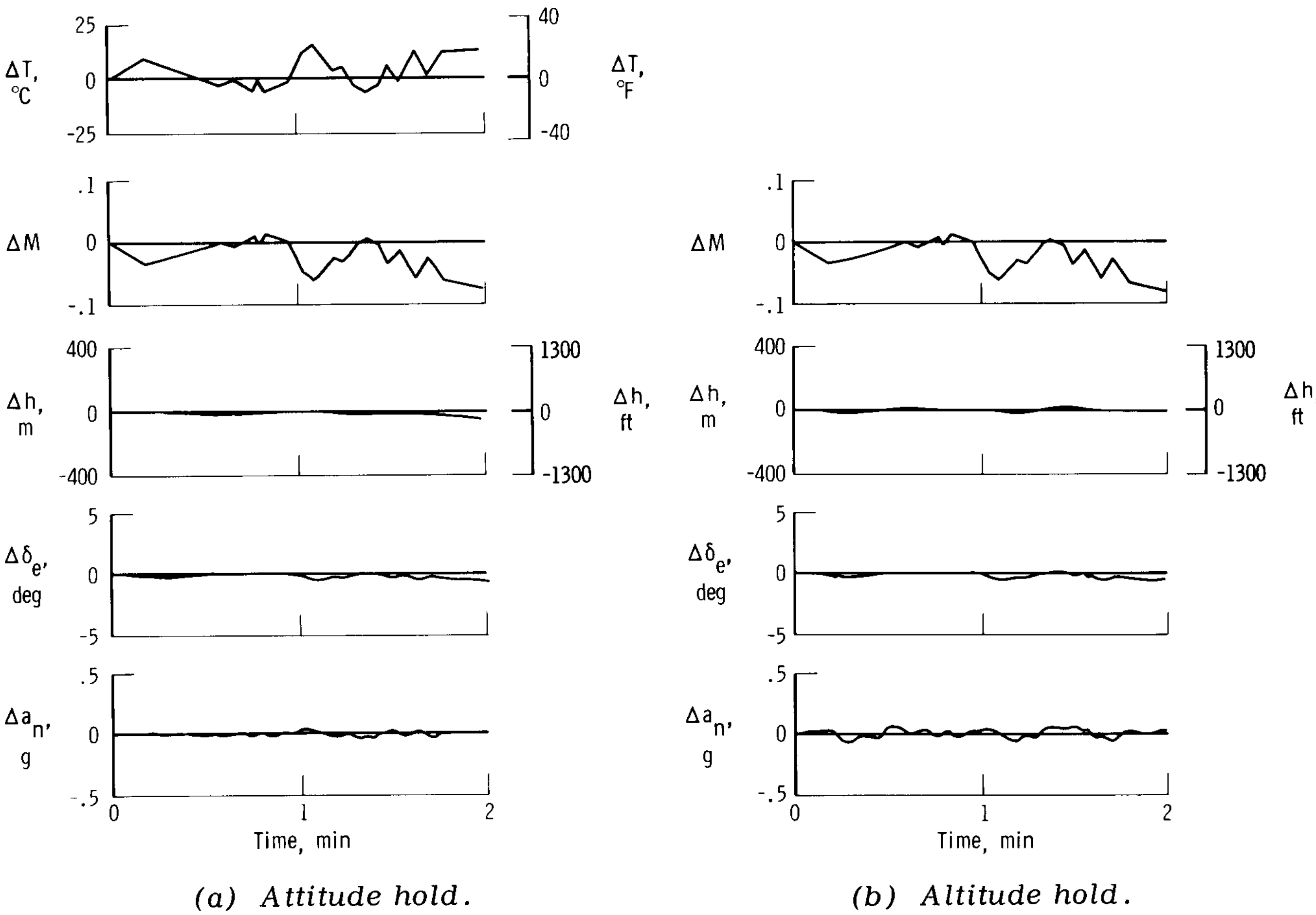
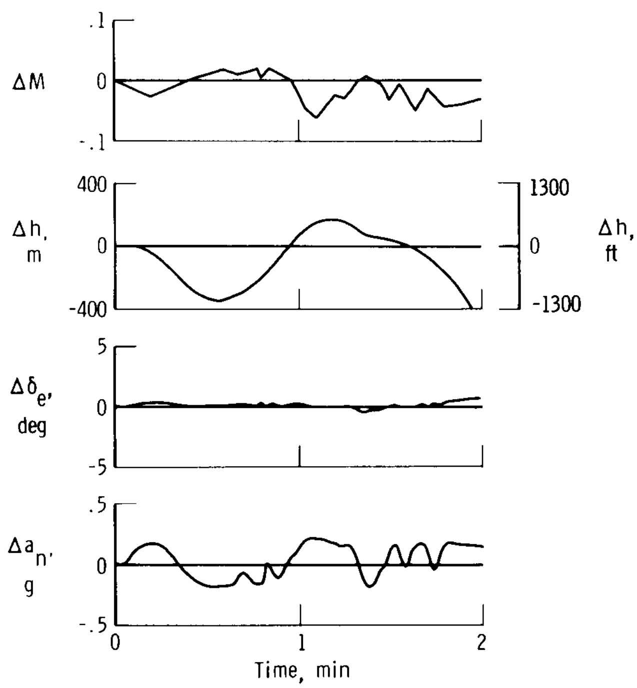


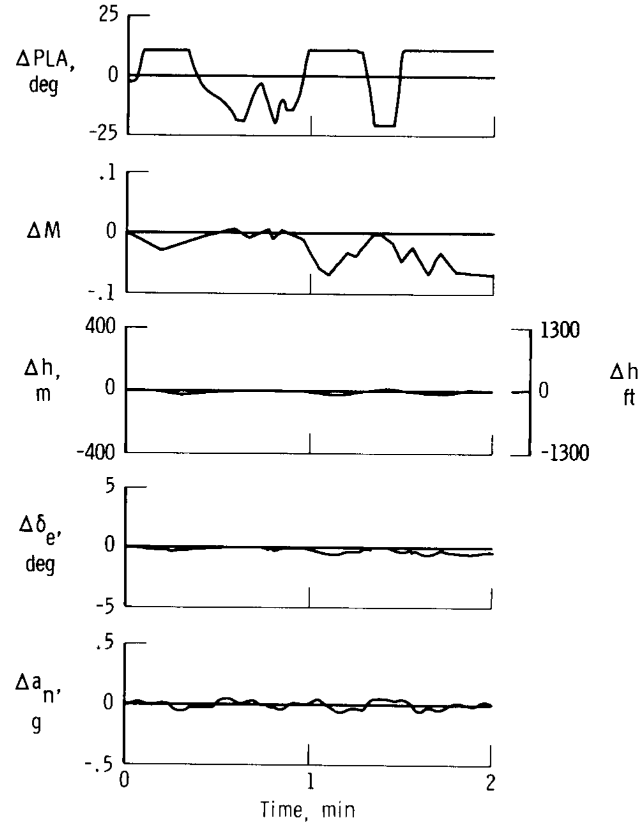
Figure 11. Simulated aircraft response to extreme temperature variations with different types of control.

In-Flight Performance of the Autothrottle System

Flight test data obtained at Mach 3.0 and an altitude of 22,100 meters (72,500 feet) with the autothrottle in Mach hold and the pitch autopilot in altitude hold are presented in figure 12. This particular time history illustrates a number of autothrottle response characteristics. The system is in altitude hold at the start of the time history, and the aircraft is stabilized at a bank angle of 36°. Approximately 30 seconds into the time history, the autothrottle Mach hold is engaged, and shortly thereafter the aircraft is rolled to wings level. Mach number is well controlled through roll transition and acquisition of stabilized wings-level flight (ΔM = ±0.01). Approximately 2.5 minutes into the run, the pilot commanded a



(c) Mach hold.



(d) Autothrottle Mach hold and altitude hold.

Figure 11. Concluded.

0.023 Mach number reduction (via a potentiometer in the cockpit). Although aircraft response is not rapid, Mach number gradually decreases to the commanded level. Response is relatively slow, since actuator authority is limited and the error signal has already commanded the minimum PLA. The desired altitude is perfectly maintained before and after rollout, although 24.4 meters (80 feet) were gained during the rollout transition. The accuracy of altitude control is particularly noteworthy in view of the large power changes commanded by the autothrottle Mach hold system. Ride qualities, as indicated by normal acceleration, are much improved over the conventional Mach hold case (fig. 8).

A second time history showing autothrottle Mach hold is presented in figure 13. In this time history, the autothrottle Mach hold and altitude hold were engaged with wings level. After approximately 1.5 minutes, the aircraft was rolled into a 30°

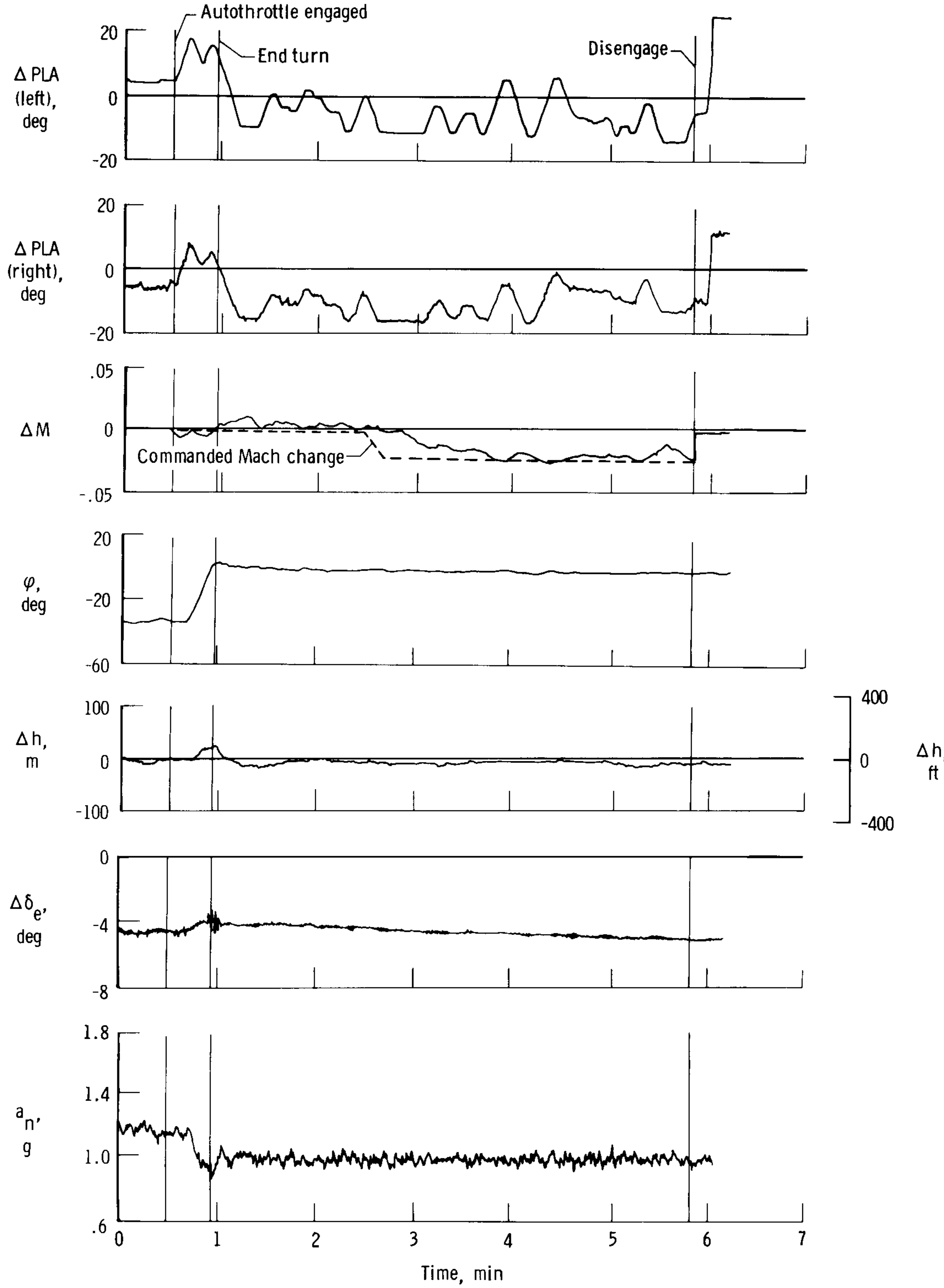


Figure 12. Autothrottle Mach hold and altitude hold. $M \approx 3.0$; $h \approx 22,100$ m (72,500 ft).

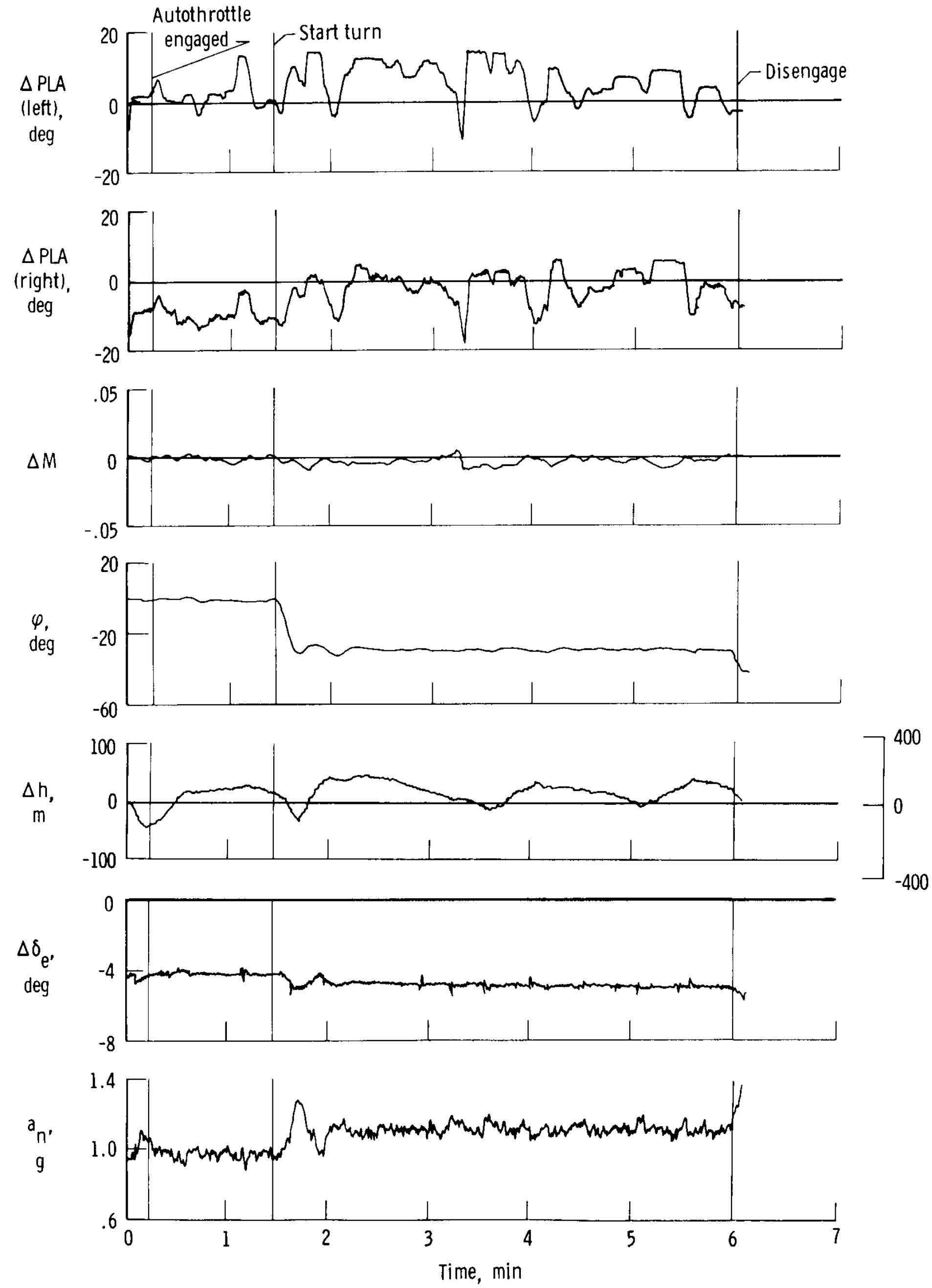


Figure 13. Autothrottle Mach hold and altitude hold. $M \approx 2.8$; $h \approx 21{,}030$ *m (69,000 ft).*

banked turn and remained in the turn for the duration of the run. Mach number was controlled within ±0.01, and altitude control was good.

When used in the KEAS hold mode, the autothrottle provides speed control which, when used in conjunction with altitude hold, is theoretically equivalent to Mach hold. In this configuration, and at similar flight conditions as for figure 13, KEAS was controlled to ±2 KEAS of the desired airspeed.

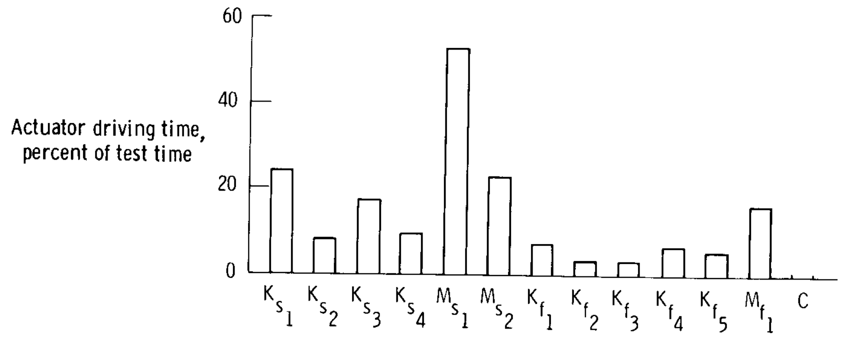
In addition to the two time histories just discussed, 25 other autothrottle tests were made (including both Mach and KEAS hold). Of these tests, 12 were selected for statistical analysis. Tests were eliminated for purposes of analysis if they were short or if they were made at the same time as other types of tests that would affect statistical comparisons. Although the report to this point has dealt mainly with the autothrottle Mach hold concept, the actual flight tests of the autothrottle were divided approximately evenly between Mach and KEAS hold. Nine of the 12 tests selected for analysis happen to be for the KEAS hold mode; however, as was mentioned previously, with altitude hold engaged the two modes should produce equivalent results. The tests analyzed range from 200 to 1200 seconds in duration and include both fast and slow actuators.

The results of the statistical analysis are presented in figure 14. Table 1 lists the flight test conditions and defines the symbols used in figure 14. The conventional Mach hold test in figure 8 is included in the figure for comparison. It is designated case C and contains no autothrottle activity. The time histories presented in figures 12 and 13 are included in figure 14 as cases M_{s_1} and M_{f_1}, respectively.

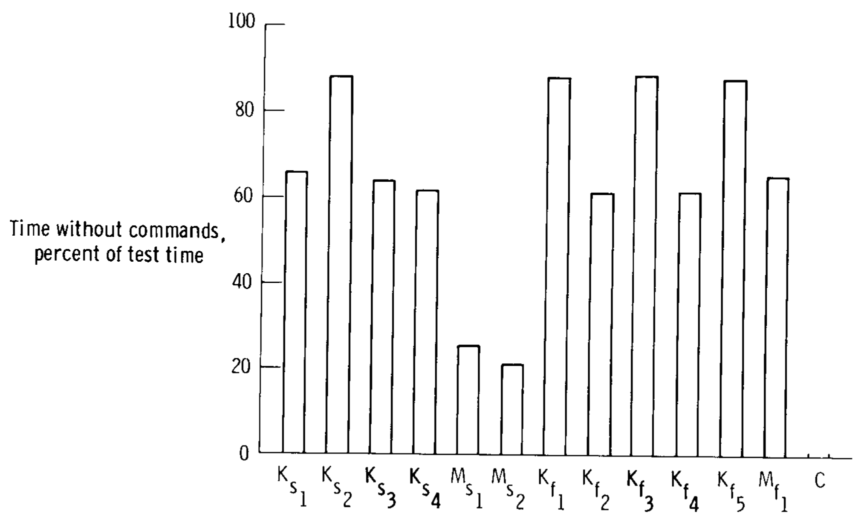
Figures 14(a) to 14(d) indicate the percentage of time the actuators spent at various conditions. The percentage of time the actuator was driving is shown in figure 14(a), whereas the percentage of time the actuator received no commands is shown in figure 14(b). The percentage of time the actuators were at the limits of their authority are shown in figures 14(c) and 14(d). Since much of the autothrottle experience was obtained in turns and the results for the turns have different characteristics than the results for level flight, the average bank angle for each time history is included in figure 14(e). The aircraft bank angle in turns is approximately 30°; therefore, absolute values of φ_{av} of 15° indicate that the test is split about evenly between level and banked flight.

The actual performance of the combined autothrottle, altitude hold system is shown in terms of the standard deviation of Mach number, KEAS, and altitude in figures 14(f), 14(g), and 14(h), respectively. The standard deviations of the PLA and elevon controls are shown in figures 14(i) and 14(j). The standard deviations of angle of attack and pitch attitude are presented in figures 14(k) and 14(l).

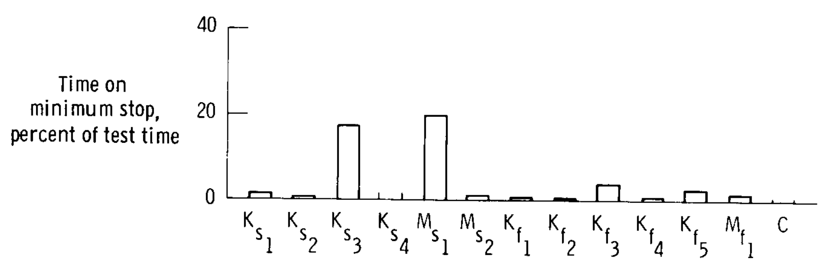
If these results are to be interpreted in an unbiased manner, nearly all of the parts of figure 14 must be considered simultaneously. For example, bank angles other than zero produce larger than normal values of standard deviation in all of the parameters that are affected by the resulting changes in aircraft trim conditions. A few interpretations of the results follow.



(a) Percentage of test time with actuator driving.

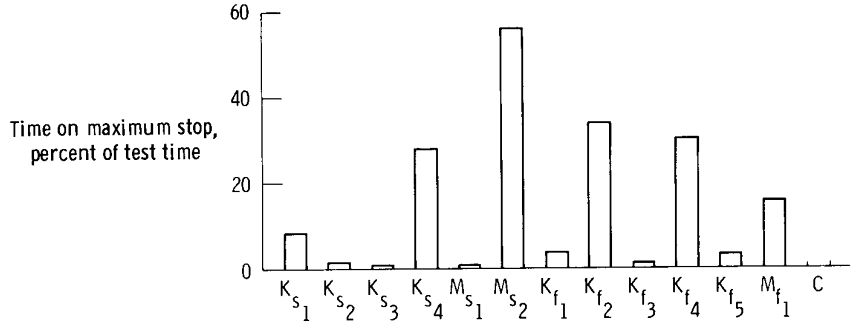


(b) Percentage of test time with actuator not commanded.

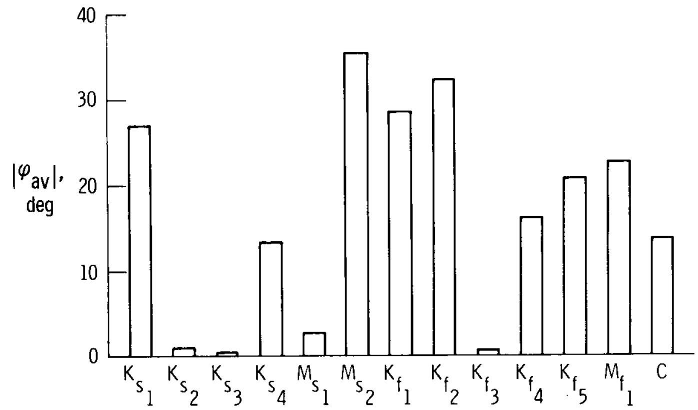


(c) Percentage of test time with actuator on minimum stop.

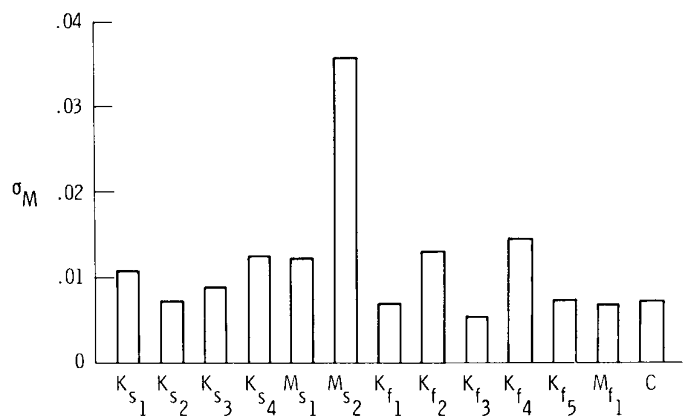
Figure 14. Statistical characteristics of autothrottle system tests.



(d) Percentage of test time with actuator on maximum stop.

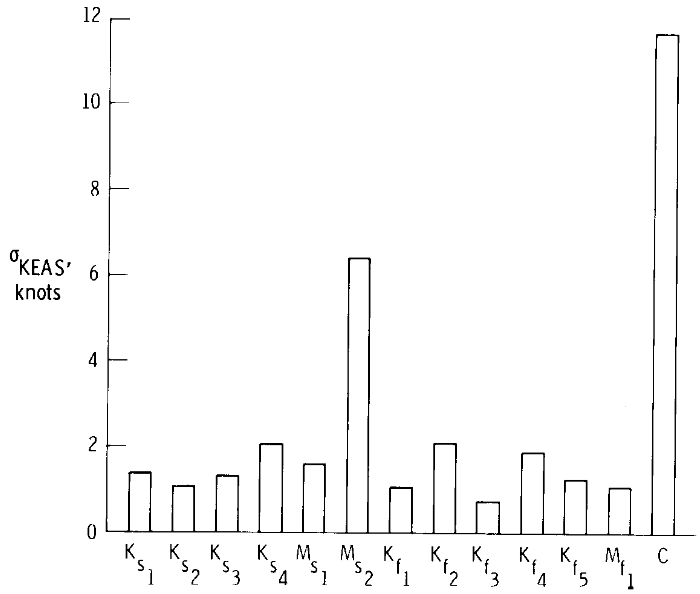


(e) Absolute value of average bank angle.

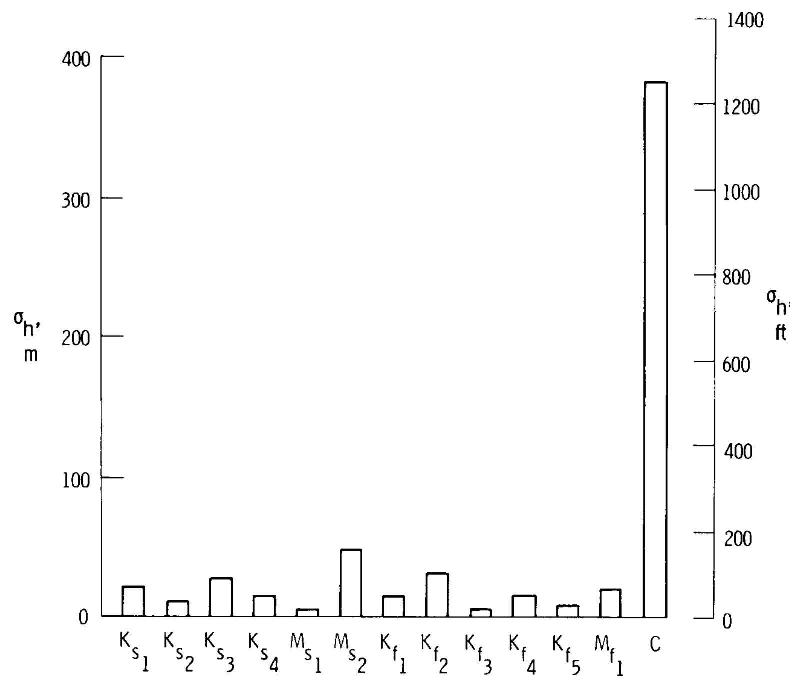


(f) Standard deviation of Mach number.

Figure 14. Continued.

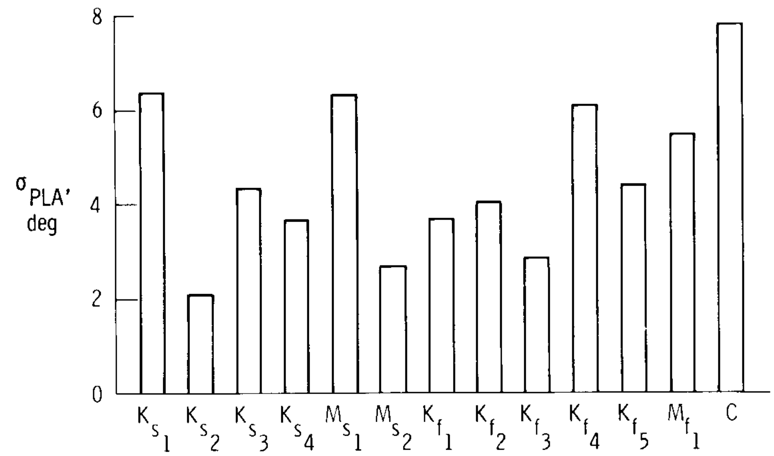


(g) Standard deviation of KEAS.

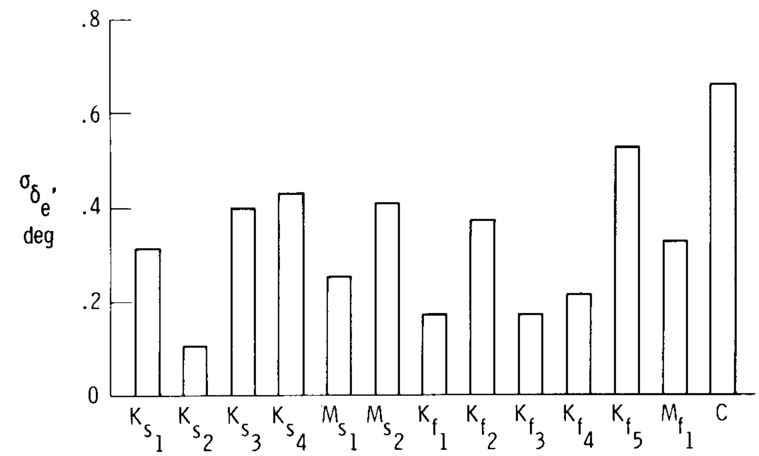


(h) Standard deviation of altitude.

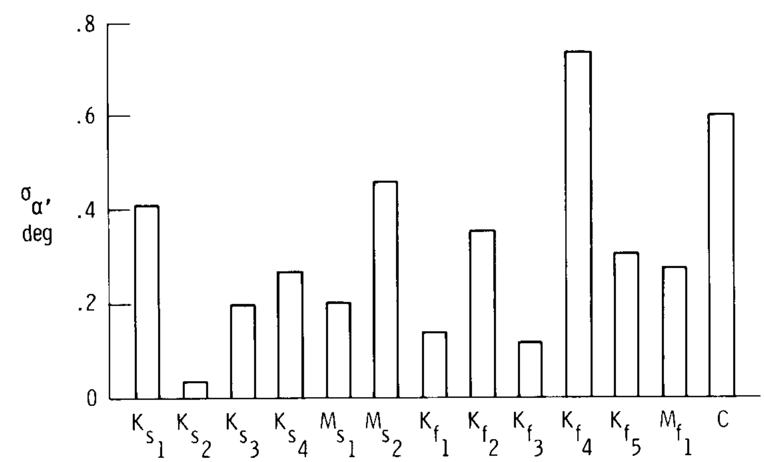
Figure 14. Continued.



(i) Standard deviation of PLA.

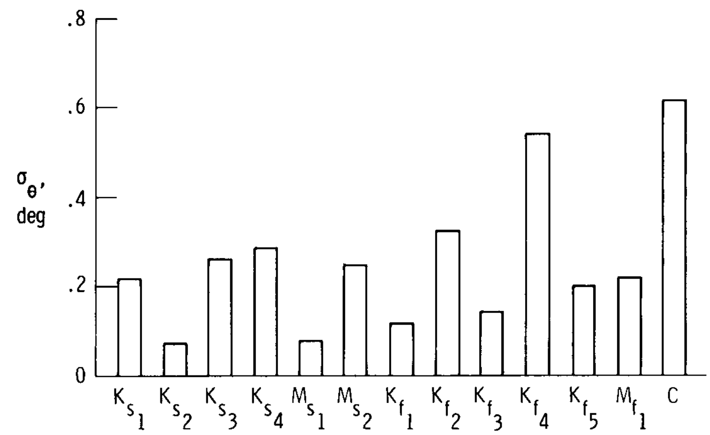


(j) Standard deviation of elevon displacement.



(k) Standard deviation of angle of attack.

Figure 14. Continued.



(l) Standard deviation of pitch attitude.

Figure 14. Concluded.

TABLE 1.—AUTOTHROTTLE FLIGHT CONDITIONS

Case number	Autothrottle mode	Actuator speed	Mach number	KEAS	Altitude, m (ft)	Test duration, sec
K_{s_1}	KEAS hold	Slow	2.85	403	21,046 (69,050)	217.8
K_{s_2}	KEAS hold	Slow	2.46	405	19,087 (62,620)	219.2
K_{s_3}	KEAS hold	Slow	2.79	408	20,653 (67,760)	1219.4
K_{s_4}	KEAS hold	Slow	2.81	402	20,918 (68,630)	1085.0
M_{s_1}	Mach hold	Slow	3.00	390	22,189 (72,800)	321.8
M_{s_2}	Mach hold	Slow	2.76	397	20,848 (68,400)	206.2
K_{f_1}	KEAS hold	Fast	2.80	395	21,070 (69,130)	218.3
K_{f_2}	KEAS hold	Fast	2.72	401	20,562 (67,460)	363.5
K_{f_3}	KEAS hold	Fast	3.00	386	22,400 (73,490)	212.0
K_{f_4}	KEAS hold	Fast	3.00	393	22,200 (72,830)	216.0
K_{f_5}	KEAS hold	Fast	2.55	430	18,818 (61,740)	639.6
M_{f_1}	Mach hold	Fast	2.81	398	21,055 (69,080)	358.2
C	----------	-----	2.85	395	21,333 (69,990)	1069.0

Case K_{s_4} (KEAS hold, slow actuator, fourth case), was approximately 18 minutes long, and KEAS has a standard deviation larger than average (fig. 14(g)). The $|\varphi_{av}|$ (fig. 14(e)) is approximately 13°, indicating that about one-half of the test time was spent in a turn. Figure 14(d) indicates that the PLA actuator was at its maximum limit for about 28 percent of the test due to the increased PLA requirements of the turn, and this accounts for the larger than average standard deviation in KEAS. It should be noted that the PLA actuator never reaches its minimum limit (fig. 14(c)). The standard deviation of the power lever angle is lower than might be expected (based on the standard deviation of KEAS), since the actuator was at its authority limit for a significant part of the time.

Case K_{s_3} (KEAS hold, slow actuator, third case) was approximately 20 minutes long, and the standard deviation in KEAS was similar to that in other tests. The average bank angle for this case indicates that the aircraft was wings level for the entire test. During approximately 18 percent of this test, the PLA actuator was at its minimum stop (fig. 14(c)) due to the lower power requirements for steady wings-level flight. The actuator was at its maximum PLA condition (fig. 14(d)) less than 1 percent of the time. The standard deviation in power lever angle (fig. 14(i)) is slightly larger than in the previous case discussed, since less time was spent at the actuator limits, allowing for more PLA activity.

Case M_{s_2} (Mach hold, slow actuator, second case) has the largest standard deviation in Mach number (as well as in KEAS) of all of the autothrottle tests analyzed. This is primarily because the test had the highest average bank angle of all tests analyzed, which in turn resulted in more time on the actuator limits than any other test analyzed.

The conventional Mach hold case (case C) was approximately 18 minutes long and had a nominal standard deviation in Mach number (fig. 14(f)). In this test, however, the standard deviation of KEAS (fig. 14(g)) was very large, and was not proportional to the standard deviation in Mach number, since altitude was not kept constant but rather was used to control Mach number. (In all the other cases in fig. 14, altitude was kept fairly constant (fig. 14(h)), so Mach number and KEAS variations were proportional to one another.) Approximately one-half of this case represented turning flight (fig. 14(e)), and as a result, a step PLA input was made by the pilot to compensate for increased load factor and angle of attack. This step PLA input accounts for the rather large standard deviation in PLA (fig. 14(i)).

The only reason the autothrottle system's performance is not completely satisfactory is that PLA activity is relatively high, as indicated by the standard deviation in PLA (fig. 14(i)). However, the primary objective of the autothrottle test program was to demonstrate good speed control with simultaneous control over altitude and good ride qualities, and in these respects the results were excellent. Consideration was given to minimizing PLA activity, but although the flight data produced higher PLA activity than anticipated, no additional effort was devoted to the problem. PLA activity could probably be reduced by a combination of gain reduction and increased filtering. A blended autcthrottle system where the high frequencies are controlled by inertial quantities and the low frequencies are controlled by air data quantities may also reduce PLA activity.

CONCLUDING REMARKS

An autothrottle system was developed and flight tested in Mach 3 cruise flight on the YF-12C aircraft. The autothrottle system was designed to control either Mach number or knots equivalent airspeed (KEAS) and to work in conjunction with a previously developed altitude hold autopilot system.

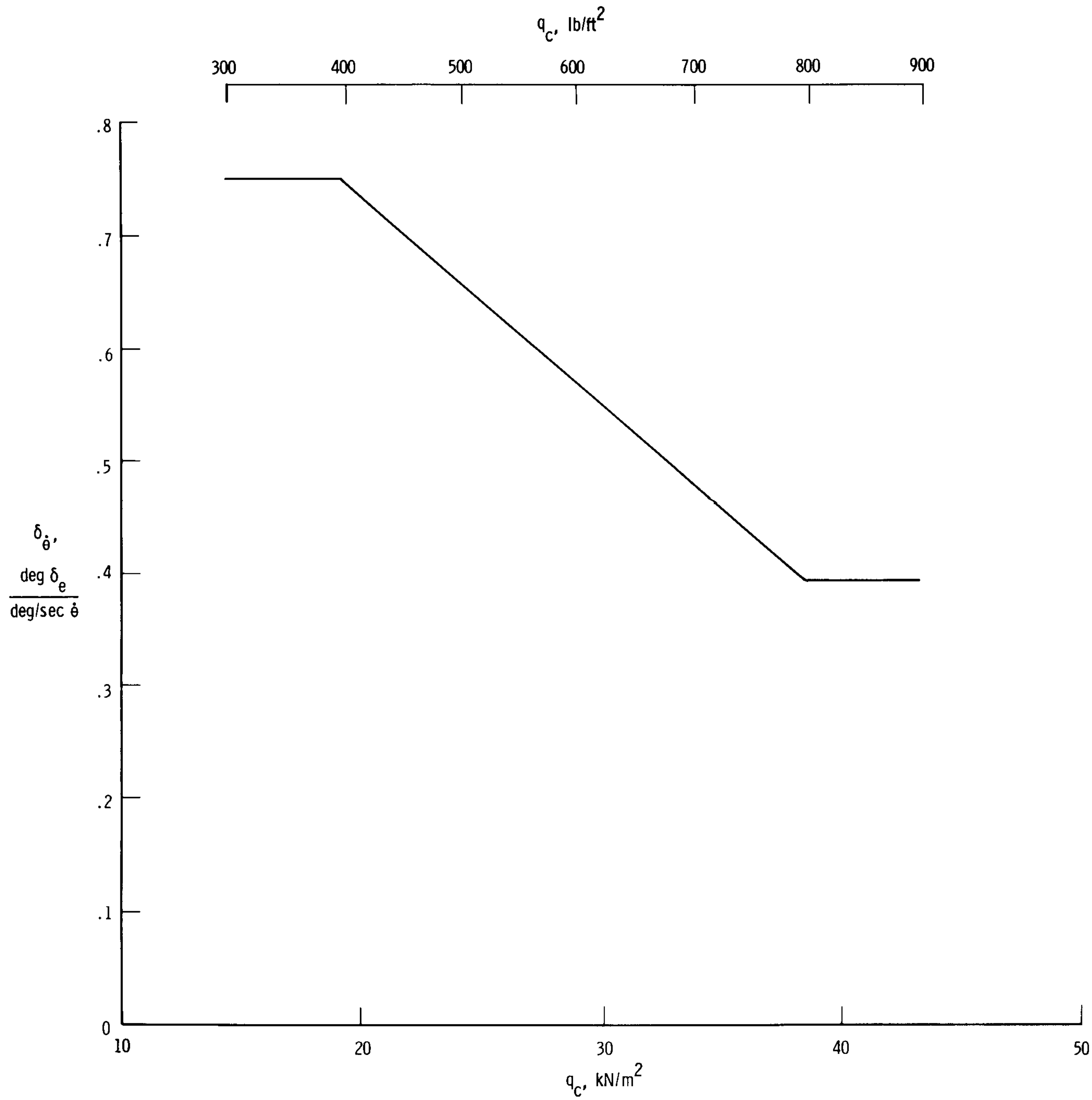
In general, the combined systems functioned excellently, with Mach number control of ±0.01 and KEAS control of ±2 KEAS at Mach 3 flight conditions. In all cases the autothrottle system was operated in conjunction with altitude hold, and in this configuration it produced significantly better ride qualities than could be obtained with the conventional Mach hold system.

National Aeronautics and Space Administration
Dryden Flight Research Center
Edwards, California, August 2, 1979

PAGE
INTENTIONALLY
LEFT
BLANK

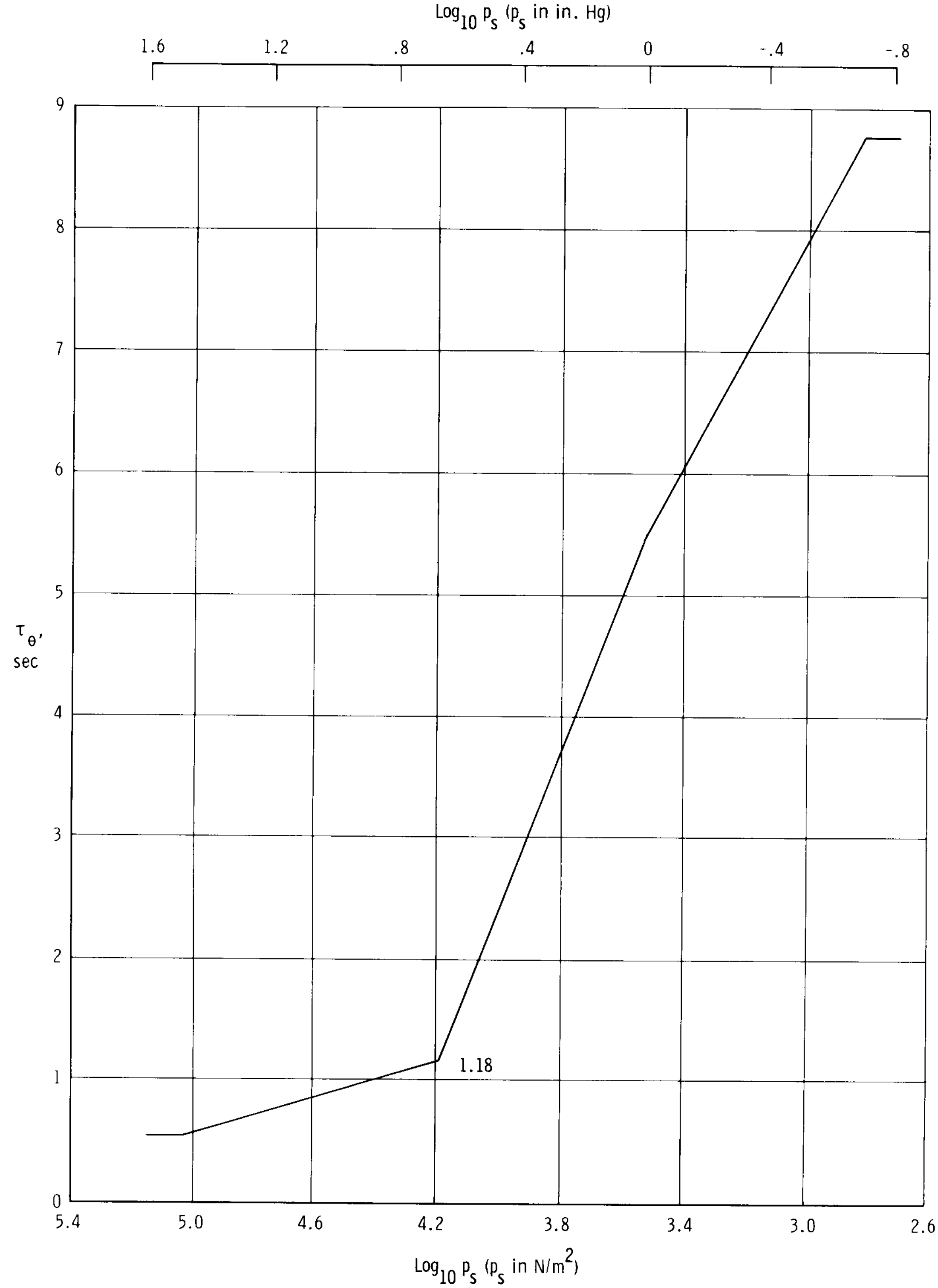
APPENDIX—AUTOPILOT SCHEDULES

Figures 15(a) to 15(g) in this appendix present the time constant and gain schedules for the YF-12C pitch-axis vehicle control system shown in figure 6.



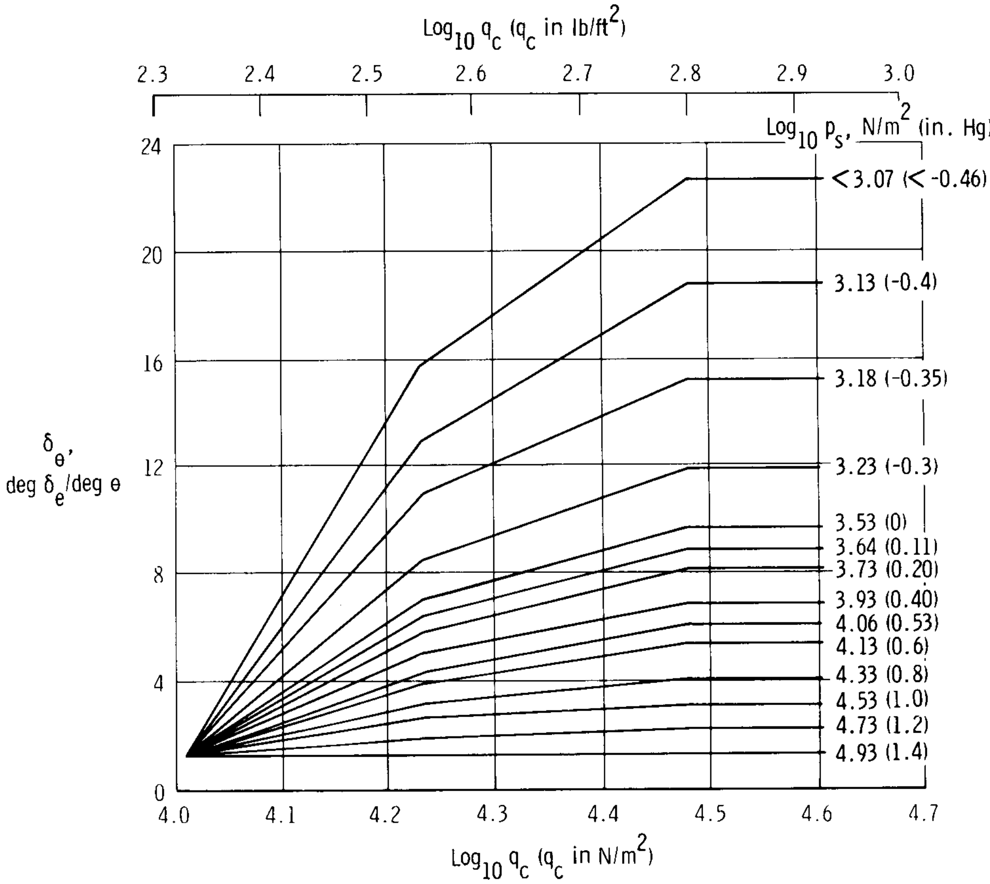
(a) Schedule 1: Pitch rate-to-elevon gain.

Figure 15. Autopilot schedules.

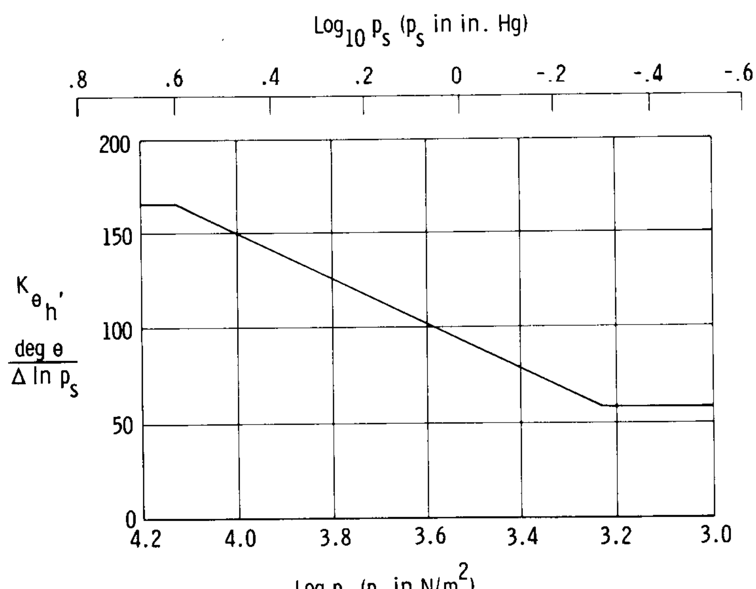


(b) Schedule 2: Pitch attitude time constant.

Figure 15. Continued.

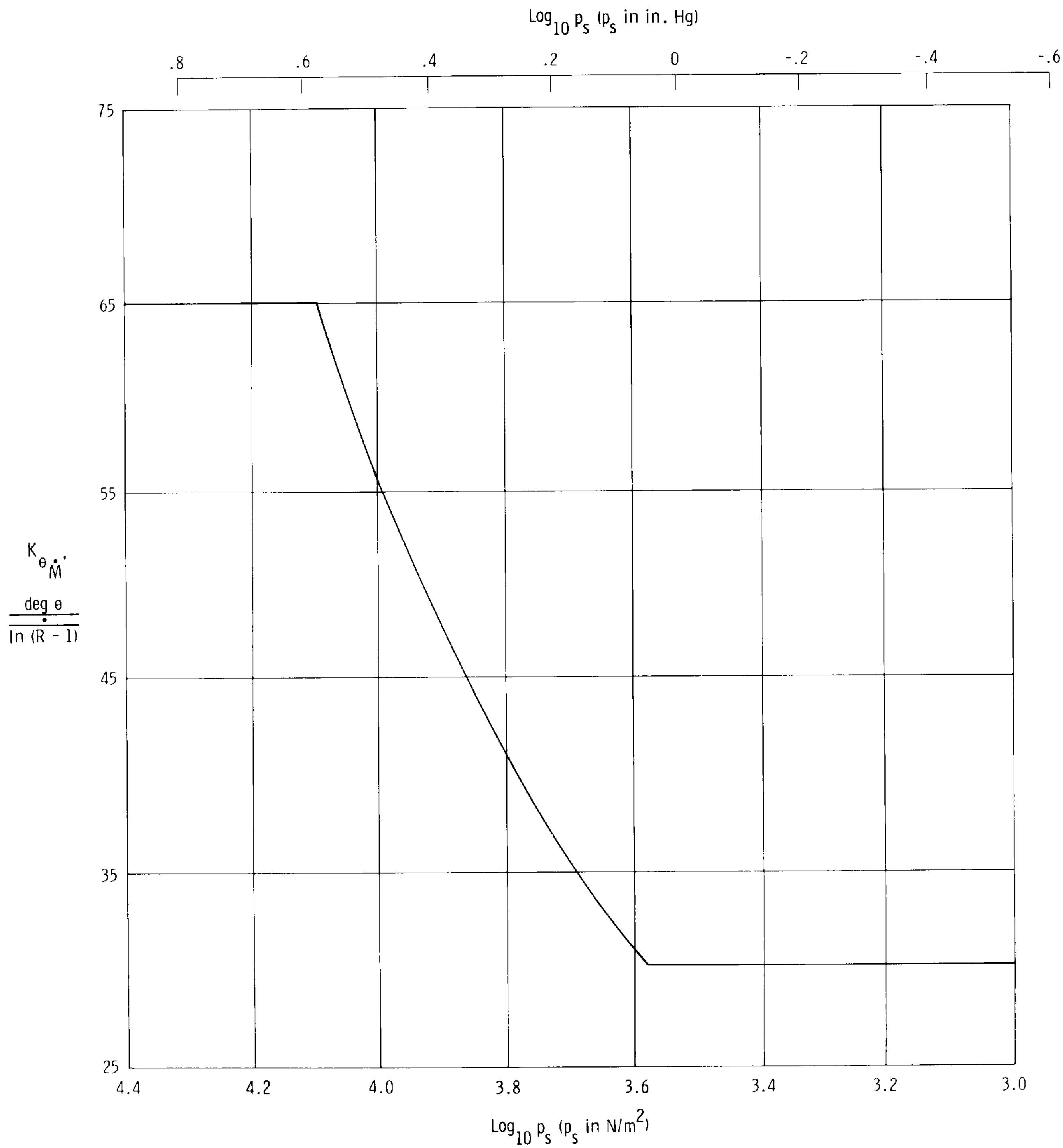


(c) Schedule 3: Pitch attitude gain.



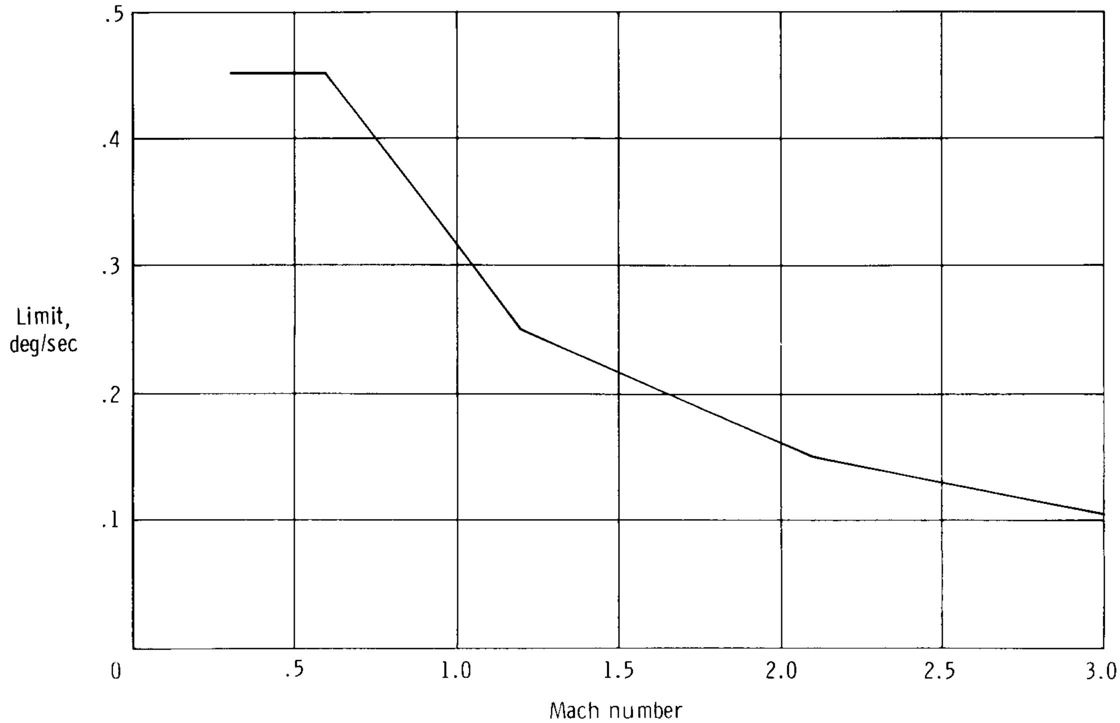
(d) Schedule 4: Altitude displacement gain.

Figure 15. Continued.

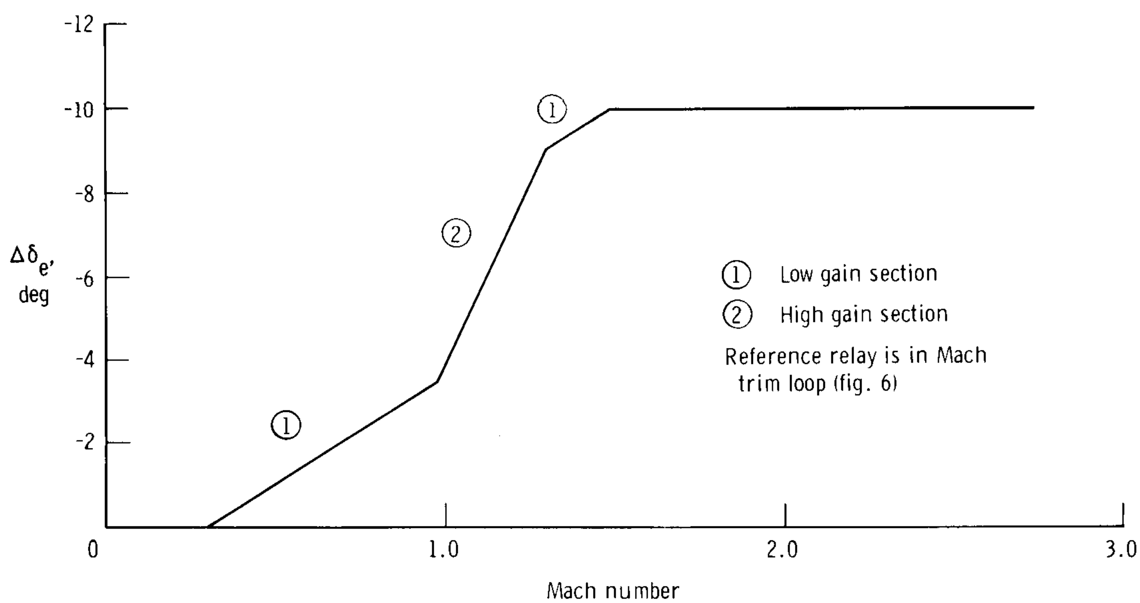


(e) Schedule 5: Mach rate gain.

Figure 15. Continued.



(f) Schedule 6: Limit of pitch rate command.



(g) Schedule 7: Mach trim compensation.

Figure 15. Concluded.

REFERENCES

1. Gilyard, Glenn B.; and Smith, John W.: Results From Flight and Simulator Studies of a Mach 3 Cruise Longitudinal Autopilot. NASA TP-1180, 1978.

2. Gilyard, Glenn B.; and Smith, John W.: Flight Experience With Altitude Hold and Mach Hold Autopilots on the YF-12 Aircraft at Mach 3. YF-12 Experiments Symposium, NASA CP-2054, Vol. 1, 1978, pp. 97-119.

3. Gilyard, Glenn B.; Berry, Donald T.; and Belte, Daumants: Analysis of a Lateral-Directional Airframe/Propulsion System Interaction. NASA TM X-2829, 1973.

4. Montoya, Earl J.: Wind-Tunnel Calibration and Requirements for In-Flight Use of Fixed Hemispherical Head Angle-of-Attack and Angle-of-Sideslip Sensors. NASA TN D-6986, 1973.

5. Gilyard, Glenn B.; and Belte, Daumants: Flight-Determined Lag of Angle-of-Attack and Angle-of-Sideslip Sensors in the YF-12A Airplane From Analysis of Dynamic Maneuvers. NASA TN D-7819, 1974.

6. Brown, Stuart C.: Computer Simulation of Aircraft Motions and Propulsion System Dynamics for the YF-12 Aircraft at Supersonic Cruise Conditions. NASA TM X-62245, 1973.

7. Schweikhard, W. G.; Gilyard, G. B.; Talbot, J. E.; and Brown, T. W.: Effects of Atmospheric Conditions on the Operating Characteristics of Supersonic Cruise Aircraft. IAF Paper 76-112, Internat. Astronaut. Federation, Oct. 1976.

1. Report No. NASA TP-1621	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DEVELOPMENT AND FLIGHT TEST RESULTS OF AN AUTOTHROTTLE CONTROL SYSTEM AT MACH 3 CRUISE		5. Report Date July 1980
		6. Performing Organization Code
7. Author(s) Glenn B. Gilyard and John J. Burken		8. Performing Organization Report No. H-1090
		10. Work Unit No.
9. Performing Organization Name and Address NASA Dryden Flight Research Center P.O. Box 273 Edwards, California 93523		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report presents flight test results obtained with the original Mach hold autopilot designed for the YF-12C airplane which uses elevator control and a newly developed Mach hold system which uses an autothrottle integrated with a previously developed altitude hold autopilot system. The autothrottle system was flight tested in Mach 3 cruise flight. The results of simulation studies are also presented.

The main objective of the autothrottle tests was to demonstrate good speed control at high Mach numbers and high altitudes while simultaneously maintaining control over altitude and good ride qualities. The autothrottle system was designed to control either Mach number or knots equivalent airspeed (KEAS).

Excellent control of Mach number (or KEAS) was obtained with the autothrottle system when combined with altitude hold. Ride qualities were also significantly better than with the conventional Mach hold system.

17. Key Words (Suggested by Author(s)) Flight control Mach control Mach 3 cruise aircraft YF-12 aircraft		18. Distribution Statement Unclassified—Unlimited Subject Category 08	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 40	22. Price* $3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1980